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Sustainability assessment through the coupling between BIM and MIVES methodologies applied in viaduct projects

MASTER FINAL THESIS

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Abstract

One of the most important challenges in the architecture, engineering and construction industry is to implement sustainable development. Sustainable development seeks not to compromise the ability of future generations to meet their needs. The implementation of sustainable development involves the evaluation of the economic, environmental and social sustainability of a project. There are different methodologies that allow carrying out these evaluations or developing projects in a comprehensive way. Among the tools for the evaluation of sustainability, the "Integrated Value Model for Sustainability Assessment" (MIVES) stands out since it allows the evaluation of projects or parts thereof, considering economic, environmental and social aspects. On the other hand, the Building Information Modeling (BIM) methodology allows the joint work of all the stakeholders of a project. The integration of BIM and MIVES for the evaluation of sustainability has not been found in the literature. The objective is to develop a new methodology for evaluating sustainability in viaduct projects through the integration between BIM and MIVES. The proposed methodology is developed for viaducts since they are large-scale engineering works and involve the use of a large amount and diversity of resources. To meet this objective, a two-step methodology is applied. First, the new proposal for the evaluation of sustainability is developed and subsequently validated by means of a case study. The proposed methodology has been proposed around the use and analysis of data that must be correct and complete to have results that reflect the reality of the projects.

Contents

List of Figures

List of Tables

Chapter 1

Research problem and objectives

1.1 Problem definition

In 1987 the Report of the World Commission on Environment and Development: Our Common Future defined the term sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [5]. Sustainable development is the benchmark for achieving human development goals in a way that meets the needs of the present without compromising the ability of future generations. The implementation of sustainable development involves the evaluation of sustainability in its three dimensions, economic, environmental and social. Economic sustainability refers to economic well-being and growth through the use of resources efficiently to ensure equitable growth and equal opportunities. Environmental sustainability broaches to the use of natural resources without compromising the needs of future generations. Social sustainability introduces the relationship between people and the project, the generation of employment, the safety and health of people and to take care of social welfare. The sustainability assessment is designed to reduce the negatives and maximize the positives economic, environmental and social impacts of a project. A correct assessment of sustainability requires correct and complete information about a project.

The “Architecture, Engineering and Construction” (AEC) industry is one of the industries with the highest consumption of natural resources and with a high degree of environmental and social impact. Day by day the AEC industry presents problems that have to be solved but the decisions that must be taken have limited time and are of great responsibility. Commonly for decision-making, technical and economic criteria are applied, leaving aside environmental and social criteria. Incorporating sustainable development within the AEC industry implies finding solutions that, in addition to meeting technical and economic criteria, meet environmental and social criteria [5]. There are many tools for decision-making regarding sustainable development by assessment sustainability [6]. Depending on the tool used sustainability assessment can be carried out on the entire project or on parts of it. Among these tools it is to highlight the “Integrated Value Model for Sustainability Assessment” (MIVES) developed in 2009 [7]. MIVES allows a multi-criteria analysis that considers the economic, environmental and social dimensions of sustainability. In Spain, MIVES is currently one of the most utilized methods to assess sustainability. Another problem that the AEC industry has is the lack of integration among stakeholders which leads to errors due to lack of communication and interoperability. “Building Information Modeling” (BIM) is a methodology that allows solving these problems. BIM concept started in 1984 as a three-dimensional modeling program [8].

BIM methodology allows all the stakeholders of a project to work around the same axis, this allows generating complete and correct information about a project. In the last years uses and applications of BIM have increased since governments around the world began requesting this methodology in their projects [9].

Existing tools to assess sustainability whether old or new are not directly compatible with the BIM methodology [10]. No studies that combine the BIM and MIVES methodologies are presented in the literature. This master's thesis aims to fill this gap by coupling BIM with MIVES to ease the sustainability assessment in viaduct projects. Viaducts are large-scale engineering works and have significant implications. The construction of a viaduct involves various construction processes and the use of different structural materials leading to greater sources of uncertainty. Furthermore, the viaduct projects imply the relationship between different fields of engineering, such as geological, geotechnical, hydraulic, hydrological, highway, structural and construction.

1.2 Objectives

The main objective pursued with this master's thesis and development of this research is to propose and validate a new methodology whose main characteristic is the link between the BIM and MIVES methodology for sustainability assessment in viaduct projects. The aim is to obtain an index of the viaduct that represents sustainable development based on information valued in three dimensions, economic, environmental and social.

Determining in detail an index that represents sustainable development requires specific studies to improve the estimation of certain indicators. In any case, the methodology to be developed seeks to be a first approach for the joint use of BIM and MIVES for the evaluation of sustainability in viaduct projects.

To achieve the general objective, the following specific objectives have been raised:

- Through a bibliographic review of the BIM and MIVES methodologies, find a way to merge them.
- Define indicators that allow analyzing the projects of viaducts in an economic, social and environmental way. Each aspect can be defined with an infinite number of indicators. However, the intention is to select the most representative ones.
- Define a function that allows quantifying the selected indicators in a dimensionless way and assigning a weight that represents their importance within the evaluation.
- Evaluate the sustainability index for the case study and analyze it in different scenarios.

1.3 Project Time-line

The time-line (figure 1.1) to the development of this research could be described as follow:

- **Literature review:** The objective of this activity was to carry out the current state of the art regarding the methodologies for sustainability analysis, especially the MIVES methodology and, on the other hand, the BIM methodology. The literature review aimed to provide a theoretical basis for the proposal of the new methodology based on the adaptation of BIM and MIVES.

- **BIM formation:** The use of the BIM methodology requires training for its implementation in projects, modeling and obtaining results. This activity was carried out through online modeling courses and face-to-face classes within the university. The training allowed to develop the virtual model for both the academic exercise and the case study. Within this activity, the way to couple BIM with MIVES was determined.

- **BIM academic modeling:** The modeling of an academic exercise allowed to consolidate the training and knowledge acquired on BIM modeling. It also served to test the proposed new methodology.

- **MIVES academic exercise:** The purpose of this activity was to develop the decision-making tree of the MIVES methodology to determine the indicators that were included in the BIM model of the academic exercise.

- **MIVES case study:** The intention of this activity was to apply the MIVES methodology to the case study presented. With the experience gained from the academic exercise and the development of the case study, the decision-making tree that was included in the BIM modeling was consolidated. At the end of this activity, the sustainability index was obtained with the new proposed methodology.

- **BIM case study modeling:** The target of the case study modeling was to obtain a virtual model that contains the necessary information to apply the MIVES methodology using the new proposed methodology. The modeling was carried out based on the plans and technical specifications of the project.

- **Coupling between BIM and MIVES:** The objective of this activity was to determine the basis of the new methodology. This activity was developed throughout the previous activities. Without the previous activities, it would not have been possible to consolidate the coupling between BIM and MIVES to propose the new methodology. The case study allowed to validate the proposed methodology.

- **Academic writing:** The point of this activity was to develop this document. The document presents the activities described above, its theoretical basis and the new proposed methodology applied to the case study.

All the activities presented have been developed under the guidance of the advisors.

1.4 Thesis organization

A two-step methodology is adopted, first the development of BIM and MIVES as a framework to determine the relationship between them and second the application of the framework to the case study called “Las Arenas Viaduct” located in Terrassa, Spain.

The thesis is structured in 5 chapters that follow a process of development of the objectives mentioned above.

- **Chapter 1:** defines the problem and justify the investigation. Presents the objectives and activities developed.

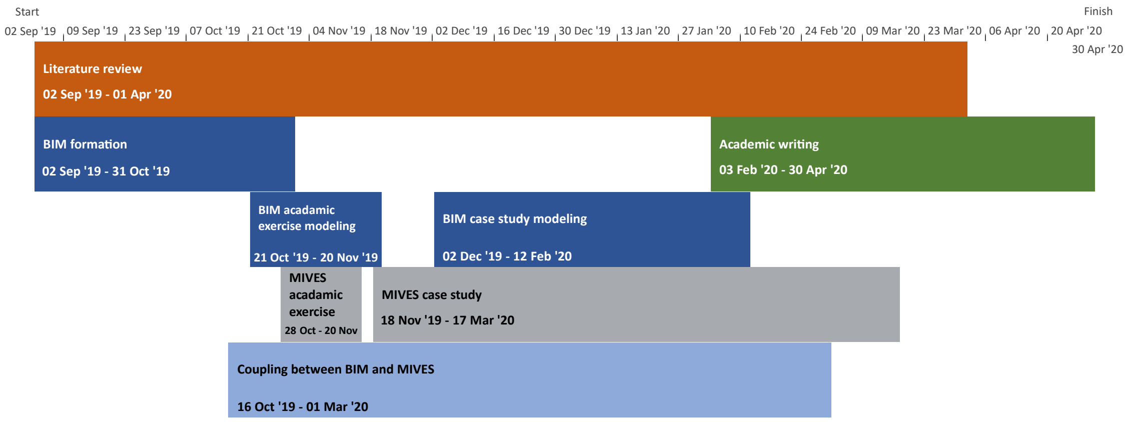


Figure 1.1: Project development time line.

- **Chapter 2:** reviews the state of the art. Includes a concise report of the methodologies to assess sustainability and the full description of the methodologies to be used in this investigation.
- **Chapter 3:** proposes a new methodology for evaluating sustainability in viaduct projects through the coupling of BIM and MIVES.
- **Chapter 4:** introduces the case study and its characteristics. It includes the application and evaluation of the methodology proposed in Chapter 3. It presents the obtained sustainability index and its variation in different scenarios.
- **Chapter 5:** presents the conclusions of this work. Future research lines are proposed to expand the usefulness of the proposed methodology.

Chapter 2

State of the Art

2.1 Introduction

Architecture, Engineering and Construction (AEC) industry is the least digitalized industry, traditional methods still prevail and technology adoption is low compared to other industries such as automotive or textile [11].

AEC industry is consuming about 50% of the material resources coming from nature, 40% of energy consumed and it is responsible for 50% of total waste generated [12]. These numbers emphasize the importance of implementing sustainability through optimizing the use of raw materials, as well as the efficiency and effectiveness of the processes within the AEC industry.

A sustainability indicator is a qualitative, quantitative or descriptive expression that provides information about economic, environmental and social aspects that allow adequates monitoring and evaluation of policies, programs and actions that guarantee the conservation of the environment, community well-being and economic growth. There are different methods to measure and quantify sustainability within the AEC industry. This chapter presents the state of the art regarding the methodologies for evaluating sustainability and fully introduces the MIVES methodology. The second part of the chapter describes BIM methodology with an emphasis on the aspects necessary for coupling with MIVES.

2.2 Sustainability assessment methods applicable to structures

Several methods and tools to sustainability assessment allow taking into account the economic, environmental and social dimensions of sustainability. Nevertheless, although these tools can provide a global sustainability index (or grade) for buildings or structural systems, most of them are not meant to assess specific structural parts [13].

In the following sections, the most common tools in the literature for evaluating sustainability are presented. Table 2.1 compares the different methods and their applications.

2.2.1 BREEAM

“Building Research Establishment Environmental Assessment Method” (BREEAM) created by the “Building Research Establishment” (BRE) in 1990, is a method to assess sustainability in masterplan projects, infrastructure and buildings. Sets standards for the environmental performance of buildings through the design, specification, construction and operation phases and can be applied to new developments or refurbishment schemes [14].

It focuses on scoring for over 50 different criteria, which are grouped in the following categories: energy, land use and ecology, water, health and wellbeing, pollution, transport, materials, waste and management. The relation expressed in percentage for each category between the points assigned related to the points available is calculated. This relation is weighed with values defined by professionals and experts. Finally, the global value is obtained and represents a satisfaction grade, this grade is compared with a scale of five results that represents the degree of BREEAM satisfaction.

2.2.2 LEED

“The Leadership in Energy and Environmental Design” (LEED) developed and certified by the “U.S. Green Building Council” (USGBC) in 1998, is a certification program and international reference point for high-performance sustainable building design, construction and operation [15].

The method consists of point allocation to score green building design and construction through 60 indicators classified in the following categories: sustainable sites, water efficiency, energy and atmosphere, material and resources, indoor environmental quality, innovation, regional priority and location and transportation. The number of points obtained allows achieving one of the followings levels of certification: LEED, silver level, gold level or platinum [16].

2.2.3 DGNB

“German Sustainable Building Council” in German (DGNB) developed by the German Sustainable Building Council in 2008, is a certificate for green building [17].

The DGNB System covers all of the key aspects of sustainable building: environmental, economic, socio-cultural and functional aspects, technology, processes and site. These aspects include 42 sustainability criteria that are evaluated to get a final score which allows obtaining one of the following certifications: bronze, silver or gold. The assessments are always based on the entire life cycle of a building

2.2.4 CEEQUAL

“The Civil Engineering Environmental Quality Assessment and Awards Scheme” (CEEQUAL) iniated by the “Institution of Civil Engineers” (ICE) in 1999 is the sustainability and rating methodology for assessment of all types of civil engineering, infrastructure, landscaping and public realm projects and contracts [18]. Since 2015 CEEQUAL is part of the BREEAM family of schemes.

CEEQUAL scheme uses a points-scoring-based assessment to 200 questions relating to the environmental and social aspects of a project. The obtained points can achieve the following CEEQUAL awards: pass, good, very good and excellent.

2.2.5 MIVES

"Integrated Value Model for Sustainability Assessment" (MIVES) is a multi-criteria decision making MCDM) approach that enables the sustainability assessment of processes and products minimizing the subjectivity associated with the indicators involved [13]. To this end, it considers value functions [19, 20, 21] and an Analytic Hierarchy Process (AHP) [2]. Additionally, statistical methods have been developed to properly account for the inherent uncertainties in order to maximize both the robustness and reliability of the results [22, 23].

Table 2.1: Sustainability assessment methods.

Method	Name	Year	Assessment criteria	Results scale	Examples of applications	Type of Projects	References
BREEAM	Building Research Establishment Environmental Assessment Method	1990	50	Pass Good Very Good Excellent Outstanding	Construction projects Offices Sustainable Homes	Buildings Construction Buildings Refurbishment Domestic Refurbishment Infrastructure New Construction	[14, 24, 25, 26, 27]
LEED	The Leadership in Energy and Environmental Design	1998	60	LEED Silver Gold Platinum	Existing buildings Green Buildings Construction	Building Design and Construction Building Operations + Maintenance Interior Design + Construction Neighborhood Development	[15, 28, 29, 30, 31]
DGNB	German Sustainable Building Council	2008	42	Bronze Silver Gold	Industrial Campus Logistics Centers	Buildings and urban districts	[17, 32, 33, 34, 35, 36]
CEEQUAL	The Civil Engineering Environmental Quality Assessment and Awards Scheme	1999	200	Pass Good Very Good Excellent	Infrastructure Materials Energy	Civil Engineering Projects	[18, 37, 38, 39, 40]
MIVES	Integrated Value Model for Sustainability Assessment	2009	N/A	0 - 1	Energy Urban Edifices Building systems Infrastructure	Engineering Projects	[7, 41, 42, 43, 13, 44]

In this work, MIVES methodology was chosen because allows very good evaluating specific structural parts such as columns, beams, or slabs as well as obtain a global sustainability index. This method considers the three sustainability dimensions as well as stakeholders satisfaction.

In the following section, a more detailed review of this methodology is presented.

2.3 MIVES

In order to assess sustainability in its three dimensions, economic, environmental and social, it is necessary to carry out a multi-criteria analysis using a methodology that enables these requirements to be met. MIVES allows the evaluation of sustainability in all its dimensions through the homogenization of parameters.

MIVES defines three levels of aspects that define the decision framework known as the decision-making tree (figure 2.1), these levels are requirements, criteria and indicators. Firstly, as a general part, the requirements match the three dimensions of sustainability. Then, criteria are aspects that cannot be directly evaluated and are found in the middle part of the decision framework. Finally, the indicators are the ones that can be quantified by representing each criterion and is the most specific part of the analysis framework.

The main characteristics of the indicators chosen in the decision-making tree must be [45]:

- **Representative:** The selected aspects must be representative of the decision that you want to drink. The indicators must represent a large part of the requirements and criteria to which they belong.

- **Discriminant:** It is important to determine indicators that represent aspects that make the alternatives different

- **Complementary:** Indicators should be defined to address all information in a complementary way. They must measure variables independent of the measures proposed by other indicators.

- **Relative:** They must be relative so as not to favor those units or elements belonging to larger groups in absolute value. It is about analyzing performance: productivity in favor of production [46].

- **Quantifiable:** The indicators can be measured using variables such as euros, square meters, days, etc. Other indicators can be represented by attributes such as high, medium, low, etc. The easiest indicators to measure should be chosen. This feature ensures that the quantifications of the different alternatives are reliable while there is less difficulty in obtaining these values.

- **Precise:**Each indicator must contain a minimum degree of uncertainty and be stated very clearly.

- **Traceable:** In this way, a future comparison of the data can be guaranteed.

It is necessary to establish value functions that allow transforming the physical units of each quantified indicator to a dimensionless unit with values between 0 and 1. To prioritize the decision-making framework, weights must be defined for each requirement, criterion and indicator assigned through the AHP applied by decision-makers [47]. One of the most important characteristics of the MIVES methodology and which makes it different from many other processes, is that the approach of the entire valuation model is prior to the creation of the alternatives [7]. Introducing the following subsections.

2.3.1 Analytic hierarchy process (AHP)

The Analytical Hierarchy Process (AHP), includes and integrates hierarchical representations, judgments and measurements. Through this process it is possible to identify relevant facts and the interrelationships that exist. The AHP allows professionals to assign numerical values to essentially abstract concepts and then deduce from these values the decisions to apply in the global framework [2].

AHP enables a comparison between pairs of homogeneous aspects, this applied in the MIVES methodology allows to compares between indicators of the same criteria, between criteria of the same requirement and finally between requirements. In this way, weights are assigned to each element between 1 and 9 according to the table 2.2 indicating the relative importance of one variable with respect to the other.

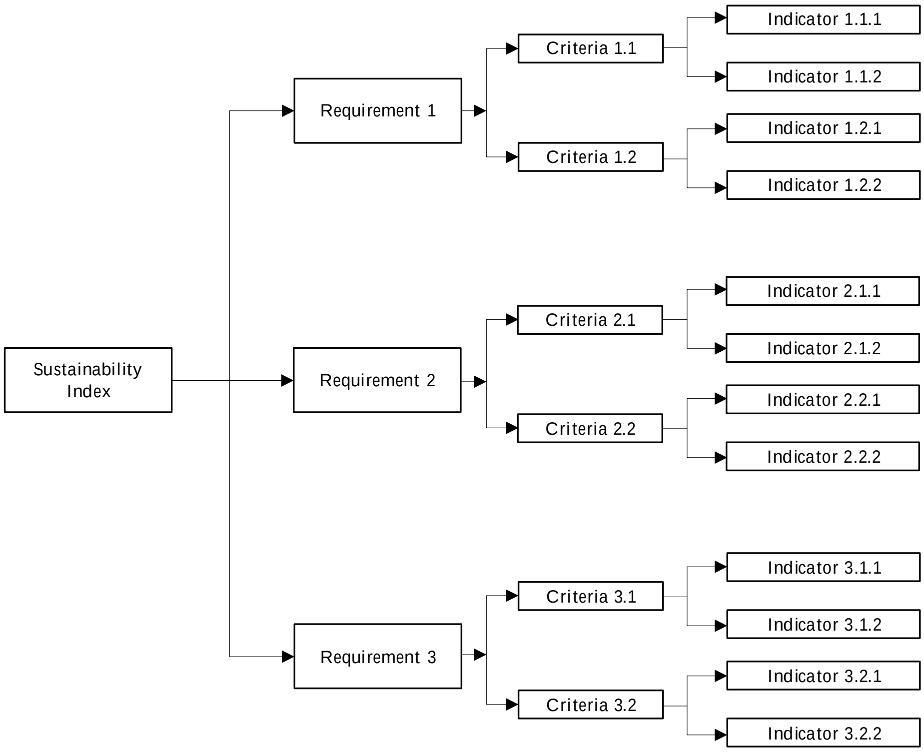


Figure 2.1: MIVES methodology decision-making tree.

Table 2.2: The fundamental scale [2]

Intensity of importance on an absolute scale	**Definition**	**Explanation**
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment strongly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocals	If activity i has one of the above number assigned to it when compared with activity j, then j has the reciprocal value when compared with i	A reasonable assumption
Rationals	Ratios arising from scale	If consistency were to be forced by obtaining n numerical values to span the matrix

With the assigned weights of each requirement i (α_i), criteria i (β_i) and indicator i (γ_i) it forms a comparison matrix (A) of dimension n by n (so A = a_{ij}) for each block of homogeneous aspects that are part of the decision-making tree. It is necessary to calculate the consistency or not of the comparison matrix since it evaluates the decisions made at the time of building the matrix, the consistency is determined by the consistency ratio. The consistency ratio (C.R) of the comparison matrix is the ratio of its consistency index (C.I) to the corresponding random index value (R.I) in the table 2.3.

Table 2.3: Random index [2]

Matrix size (n)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Random Index (R.I)	0.00	0.00	0.52	0.89	1.11	1.25	1.35	1.4	1.45	1.49

It is necessary to calculate the main eigenvector (λ_{max}) that is the multiplication between the sum of each column of the comparison matrix (A) and the weight of each element (w_j), it is calculated by the equation 2.1.

$$\lambda_{max} = \sum_{j=1}^{i} (\Sigma_{i=1}^{n} a_{ij}) w_j \tag{2.1}$$

The consistency index (C.I) is defined by the equation 2.2 which is the ratio between the principal eigenvector and the number of matrix elements (n). C.I is the measure of consistency deviation of matrix A.

$$C.I = \frac{\lambda_{max} - n}{n - 1} \tag{2.2}$$

Finally, the consistency ratio (C.R) must be less than 0.1 to ensure that the comparison matrix armed with the assigned weights is consistent (equation 2.3). In case the matrix is not consistent, the values assigned to the matrix must be changed until obtaining a consistent matrix.

$$C.R = \frac{C.I}{R.I} \leq 0.1 \tag{2.3}$$

2.3.2 Value function concept

The value function allows comparing the indicators ($_i$) with different units of measure such as cost, time, temperature, emissions, indicators quantified by attributes, etc [7]. It consists in the transformation of the indicator's units to a scale of dimensionless values that allows the weighted sum of the indicators. Each indicator must be represented with a value function between 0 and 1, null and maximum (saturation) valuation respectively.

The process to determine the value function for each indicator consists of the following four steps [20]:

1 Definition of the tendency: The value function can be increasing or decreasing. The trend depends on the characteristics of the indicator that is being evaluated. The function is increasing when the increase in the measure of the indicator leads to an increase in the satisfaction of decision-makers. The decreasing value function is opposed to the increasing one because while increasing the measure of the indicator decreases the satisfaction value. There may be value functions that have a mixed trend, this occurs in indicators that have two minimum satisfaction points and one maximum between them.

2 Definition of the minimum and maximum satisfaction points: The limits of the value function on the X-axis of each indicator are defined with the points of minimum and maximum satisfaction. These points have a satisfaction of 0 and 1 respectively. The limits defined with the satisfaction points are not necessarily the limits of the measurement values of each indicator since they normally have a wider range. These points can be defined by existing rules and regulations, previous projects, or by the value generated by different alternatives in the same project of the evaluated indicator. If there are two points of minimum satisfaction and one of maximum between them, the limits of the function must be adjusted to have a continuous increasing or decreasing function.

3 Definition of the shape: This step seeks to connect the points of minimum and maximum satisfaction by using a function with a defined shape. Four types of functions are proposed: concave, convex, linear and S-shape. These forms are the most common. The concave function is used when a rapid increase in satisfaction with respect to the variation of the indicator measure is detected. The convex function is used when there are no significant changes in the value of satisfaction by values around the measure of the indicator that represents the minimum satisfaction. The linear function represents a constant increase in satisfaction. The S-shape function detects a considerable increase in satisfaction for average values of the indicator measure and slight variations around the points of minimum and maximum satisfaction.

4 Definition of the mathematical expression: The general expression of the value function (V_i) is defined by five parameters that allow obtaining functions of all kinds of shapes: linear, concave, convex, S-shaped. It is defined with the equation 2.4 for increasing functions.

$$V_i = \ K_i \left[1 - e^{-m_i \left(\frac{\left| P_{i,x} - P_{i,min} \right|}{n_i} \right)^{A_i}} \right] \tag{2.4}$$

where:

- K_i is a factor that limits the values of the function between 0 and 1. It is defined according to the following equation:

$$K_i = \left[1 - e^{-m_i \left(\frac{\left| P_{i,max} - P_{i,min} \right|}{n_i} \right)^{A_i}} \right]^{-1} \tag{2.5}$$

- m_i defines the value of the ordinate for point n_i.
- $P_{i,x}$ abscissa of the evaluated indicator that generates an V_i value.
- $P_{i,max}$ abscissa of the indicator that generates a value equal to 1.
- $P_{i,min}$ abscissa of the indicator that generates a value equal to 0.
- n_i is a parameter that approximately defines the x-value of the point of inflection for curves with $n_i > 1$.
- A_i defines approximately the shape of the curve. If $A < 1$ the curve is concave, if $A > 1$ convex or S-shaped and if $A = 1$ it is linear.

The equation 2.4 can also be used for decreasing functions by substituting $P_{i,min}$ for $P_{i,max}$ since they take the maximum value in $P_{i,min}$ [48].

In the literature, typical values for n_i, m_i and A_i can be found according to the type of indicator analyzed. These values serve as a reference since the parameter may vary according to the decision maker's preference. If there is a lack of clarity these values can be defined through a working group [20].

Tables 2.4 and 2.5 present typical values for the parameters indicated above.

Table 2.4: Typical values of n_i, m_i and A_i for increasing value functions [3].

Function	$\boldsymbol{n_i}$	$\boldsymbol{m_i}$	$\boldsymbol{A_i}$
Linear	$n_i \approx P_{i,min}$	≈ 0.0	≈ 1.0
Convex	$P_{i,min} + \frac{P_{i,max} - P_{i,min}}{2} < n_i < P_{i,min}$	< 0.5	> 1.0
Concave	$P_{i,min} < n_i < P_{i,min} + \frac{P_{i,max} - P_{i,min}}{2}$	> 0.5	< 1.0
S-shaped	$P_{i,min} + \frac{P_{i,max} - P_{i,min}}{5} < n_i < P_{i,min} + \left(\frac{P_{i,max} - P_{i,min}}{2}\right)\frac{4}{5}$	$0.2 - 0.8$	> 1.0

Table 2.5: Typical values of n_i, m_i and A_i for increasing and decreasing functions [3].

Function	$\boldsymbol{n_i}$	$\boldsymbol{m_i}$	$\boldsymbol{A_i}$
Linear	$n_i \approx P_{i,min}$	$\approx A_0$	≈ 1.0
Convex	$P_{i,max} + \frac{P_{i,min} - P_{i,max}}{2} < n_i < P_{i,max}$	< 0.5	> 1.0
Concave	$P_{i,max} < n_i < P_{i,max} + \frac{P_{i,min} - P_{i,max}}{2}$	> 0.5	< 1.0
S-shaped	$P_{i,max} + \frac{P_{i,min} - P_{i,max}}{5} < n_i < P_{i,max} + \left(\frac{P_{i,min} - P_{i,max}}{2}\right)\frac{4}{5}$	$0.2 - 0.8$	> 1.0

2.3.3 Sustainability Index

To conclude the MIVES methodology, it is necessary to calculate the Sustainability Index (S.I) which considers all the dimensions of sustainability and its hierarchy levels within the decision-making tree. It is determined according to the equation 2.6 [3].

$$S.I = \sum_{i=1}^{i=n} \alpha_i \beta_i \gamma_i V_i(P_{i,x}) \tag{2.6}$$

The equation 2.6 takes into account the weight of each requirement (α_i), criterion (β_i), indicator (γ_i) and the value function (V_i) corresponding to each criterion.

2.3.4 MIVES Applications

MIVES has been used in different sectors to assess sustainability because of its versatility. Table 2.6 presents some applications of the MIVES methodology in the following sectors within the construction industry: Energy, Urban Planning, Buildings, Construction systems and elements and Infrastructure [3].

Table 2.6: Several applications of MIVES in the construction industry.

Level	Title	Year	Reference
Energy	Multi-criteria decision-making model for assessing the sustainability index of wind-turbine support systems: application to a new precast concrete alternative	2017	[41]
	Assessing the global sustainability of different electricity generation systems	2015	[49]
	Assessment of the sustainability of urban electric mobility through a MIVES model	2012	[50]
Urban	Mives multicriteria assessment of urbanpavement conditions: application to a case study in Barcelona	2019	[42]
	Multicriteria decision-making method for sustainable site location of post-disaster temporary housing in urban areas	2016	[51]
	Multi-Criteria Decision Making in the sustainability assessment of sewerage pipe systems	2016	[48]
	Sustainability analysis of steel fibre reinforced concrete slabs	2016	[52]
Edifices	Multi-criteria decision-making method for assessing the sustainability of post-disaster temporary housing units technologies: A case study in Bam, 2003	2016	[43]
	Integrated value model for sustainable assessment applied to technologies used to build schools in Catalonia, Spain	2012	[53]
	Industrial building design stage based on a system approach to their environmental sustainability	2010	[54]
Building systems and elements	Sustainability of column-supported RC slabs: fiber reinforcement as an alternative	2019	[13]
	Life Cycle Assessment for Sustainable Design: Classic and Low-Damage Precast Structures Subjected to Earthquakes	2018	[55]
	Sustainability applied to prefabrication	2016	[56]
	Feasibility study of the use of steel fibres for conventional and self-compacting concrete	2014	[57]
	Methodology for the evaluation and monitoring of construction procedures in an integrated and sustainable way	2014	[58]
	Integrated sustainability assessment method applied to structural concrete columns	2013	[59]
	Multivariate analysis to estimate the contribution to the sustainability of reticular slabs	2011	[60]
	A value function for assessing sustainability: application to industrial buildings	2011	[20]
	Discrimination method between different pillar solutions through sustainability criteria	2011	[61]
Infrastructure	Use of steel and polyolefin fibres in the La Canda Tunnels: applying MIVES for assessing sustainability evaluation	2018	[44]
	Can polyolefin fibre reinforced concrete improve the sustainability of a flyover bridge?	2018	[62]
	Sustainability based-approach to determine the concrete type and reinforcement configuration of TBM tunnels linings.	2017	[63]
	Road Sustainability Assessment	2017	[64]
	Sustainability as the key to prioritize investments in public infrastructures	2016	[65]
	Sustainability assessment of precast concrete segments for TBM tunnels	2016	[66]
	Knowledge-based minimization of railway infrastructures environmental impact	2016	[67]
	Sustainability analysis of reinforced concrete pipes and tubes reinforced with plastic fibres	2015	[68]
Instruction	EHE-08 Spain - Environmental sensitivity index of the concrete structure	2008	[19]

2.4 Building Information Modeling

“Building Information Modeling” (BIM) is one of the most promising developments in the Architecture, Engineering and Construction industry [69]. Although it is true that the visible part of BIM is the model, BIM it is a methodology whose main objective is to make all the stakeholders (owners, architects, engineers, contractors, subcontractors and suppliers) of a project work around the same axis.

The integration of all the stakeholders allows to obtain better results and eliminate errors caused by a lack of communication and interoperability. The final result of the BIM methodology is a virtual model that can be used in all stages of the life cycle of the building or project, such as planning, design, construction, operation and maintenance and even demolition [70].

BIM is usually confused with the use of software (Little BIM) that allows its application, but really computing is only the means for its development and implementation (Big BIM). Little BIM as a definition could say that it is the set of programs and applications that are used as tools of the methodology to generate the virtual model BIM [71]. It is the most visible part of the methodology but it is only the platform that lets stakeholders work on the development of a project around a single axis. Big BIM could be defined as the basis of the methodology [71]. It refers to the correct management of information, the management of the human and technical resources of the project and the relationship between the stakeholders [72]. This part of the BIM seeks to make the information generated available at any time and place as necessary, from the conception of the project to its operation and maintenance.

It is necessary to have a classification of the amount of information handled in the BIM methodology. Level Of Development (LOD) is an agreement to address the basic guidelines information of BIM [73]. LOD allows the players in AEC industry to clearly specify the level of content as well as the reliability of the virtual models. LOD is also associated with Level of Detail (LOI) which is the number of details included in the virtual model elements while the LOD is the degree to which stakeholders could trust in the information of the virtual model. In either case, the level being referred to, is about the richness of the component and its data, not usually its graphic complexity [74]. There are different levels of LOD: 100, 200, 300, 400 and 500 (figure 2.2). Their definitions have been developed by the “American Institute of Architects” (AIA) in the “Building Information Modeling Protocol Form” [75].

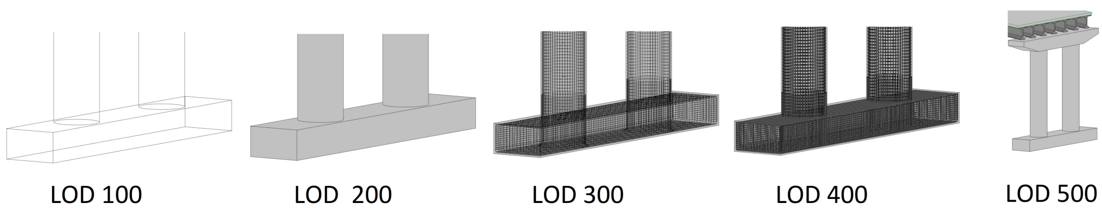


Figure 2.2: LOD illustrations of a bridge foundation.

Each level of information that can be assigned and contributes to a model describes a new dimension within the BIM. At present the experts talk about these seven dimensions:

- **1D Idea**: Needs or problems generates the initial idea of a project. This idea contains general features to solve said needs or problems, it includes initial conditions, tentative location and first design schemes.
- **2D Drawings**: It includes the characteristics of the project such as materials, structural loads, shapes, dimensions. This dimension already uses assisted design tools.
- **3D Model**: It refers to the representation of depth in the third cartesian axis, BIM allows obtaining two-dimensional information from the 3D model, not as a point of view otherwise as a model.
- **4D Time**: It includes the time parameter to each object and that allows simulations of the execution phases through the schedule of the project.
- **5D Cost**: Each object of the model has an assigned cost, which allows for detailed budget analysis and also permits predictions of the evolution of the project.
- **6D Sustainability**: It concerns everything related to the sustainability of the model. It covers aspects such as energy use, the durability of materials, environmental design, energy strategies, emissions, impacts, etc.
- **7D Facility Management**: BIM allows storing information during the execution, use and exploitation of the project. The parametric model must include maintenance plans, manuals, warranty information, etc.

Figure 2.3 presents some examples of BIM dimensions.

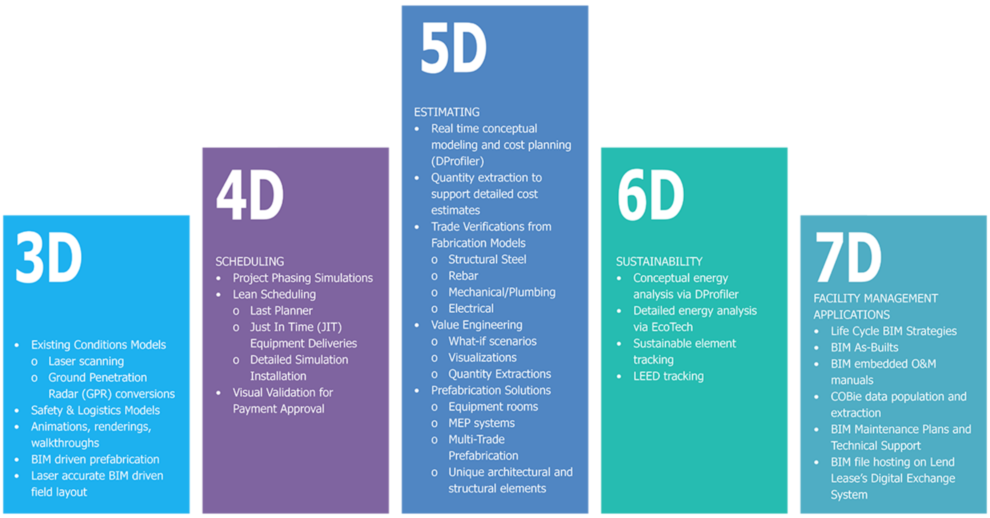


Figure 2.3: Dimensions of BIM [1].

All the information included in BIM is parametric and thereby interconnected [10]. Parametric BIM becomes a powerful design method for the AEC industry enables to search for optimal building energy solutions and design options [74]. Parametric modeling based on objects started in the 1980s, as methodology to create virtual models with constraints and parameters [69], it was proposed to integrate the domain experience into building models [76]. Objects are represented by parameters that define their geometric, physical, mechanical, economic, environmental and some other properties. The parameters of each object can be previously defined by agreements between manufacturers or can be customized to create complex geometries or define attributes necessary for further analysis [69]. BIM is related to parametric modeling as the parameters help establish and manage the relationships between virtual model objects [77]. The parameters can be the results of formulas or algorithms determined according to the needs of the project. Integrate BIM with parametric modeling improves the designs of the players of the AEC industry [74] and enables quick, interactive and real-time design changes [76]. To make clear the difference between traditional 2D objects and BIM it is necessary to know the concept of parametric objects. They are definitions that are assigned to objects and can be geometric, general data or rules that must comply. The geometry does not allow inconsistencies, the parametric rules can automatically modify the associated geometries also identify changes that violate the viability of the object and the general data can be different attributes which have the ability to be used later.

The parametric model has an associated database that contains the information generated by the base parameters for each object and the custom parameters [78]. This database allows obtaining any type of information such as quantities, dimensions, characteristics, descriptions, comments, as well as customizing fields using algebraic operations. The information in the database can be filtered, classified and customized according to the needs of the project.

BIM allows the simultaneous participation of several experts from the conception of a project on the same document, in which each expert can modify according to the role within the project. For the application of BIM, the stakeholders must have developed three basic areas that allow a project to be managed according to the BIM methodology, these areas are communication, integration and interoperability. Good communication allows to effectively manage a project. Integration has a connection with communication as they share a single virtual model on which the stakeholders work. Interoperability is necessary as stakeholders must have the ability to manage different software and use open files.

2.4.1 BIM Applications

The versatility of the BIM methodology allows several applications at different stages on a project in the AEC industry [79, 80], table 2.7 presents some BIM applications related to decision-making and sustainability.

Table 2.7: Several applications of BIM related to decision-making and sustainability assessment.

Title	Year	Reference
BIM-based assessment metrics for the functional flexibility of building designs	2019	[81]
Participatory decision-support model in the context of building structural design embedding BIM with QFD	2018	[82]
Integration of BIM and LCA: Evaluating the environmental impacts of building materials at an early stage of designing a typical office building	2017	[83]
A decision support system for the multicriteria analysis of existing stock	2017	[84]
BIM-aided Variable Fuzzy Multi-criteria Decision Making of Low-carbon Building Measures Selection	2016	[85]
Integrating decision support system (DSS) and building information modeling (BIM) to optimize the selection of sustainable building components	2015	[86]

The following paragraphs describe the main ideas of the applications presented in table 2.7.

Cavalliere et al. (2019) [81] proposes a novel approach that allows evaluating the level of flexibility of buildings automatically in the project design phases, is based on six selective criteria implemented in an integrated BIM environment with a visual programming language tools.

Eleftheriadis et al. (2018) [82] presents a new decision support model to prioritize design criteria based on specific project requirements. It integrates BIM with Quality Function Deployment for the optimization of the structural design and uses Evidence Reasoning algorithms to calculate the uncertainty of decision-makers preferences. The value of BIM integration is highlighted as it allows different design teams to easily repeat the decision process at the beginning of each project.

Najjar et al. (2017) [83] integrates BIM with the life cycle assessment (LCA) and indicates that this integration is an optimal procedure for sustainable development and environmental protection. The BIM-LCA relationship allows the assessment of the environmental impacts of construction materials from the design stage.

Corneli et al. (2017) [84] suggests a new methodology for an objective assessment of the quality of the stock of large buildings to help prioritize refurbishment actions. The methodology is based on a decision support system that evaluates buildings through the application of Bayesian Networks (BNS), the classification of buildings is done through AHP approach. BIM provides information about the buildings for each Bayesian Networks entrance. The integration between BIM and BNS allows the automatic execution of the assessment.

Chen et al. (2016) [85] develops a multi-criteria decision making model based on variable fuzzy preference ranking organization method for enrichment evaluation and assisted by BIM to select low-carbon building measures.

Jalaei et al. (2015) [86] proposes a methodology to integrate BIM with decision-making problem-solving approaches to optimize the selection of sustainable building components, a decision support system is developed through multiple-criteria decision-making techniques to help in the selection of sustainable building components. In this work, it is showed how BIM strengthens the ability of designers to assign components during the design stage of the project.

Chapter 3

New methodology for sustainability assessment in viaduct projects

3.1 Introduction

This chapter proposes a new methodology to evaluate the sustainability of viaduct projects from their design stage, taking into account the economic, environmental and social impacts. The methodology is implemented through the development of a process that simplifies and facilitates the assessment of sustainability in viaducts. The methodology emphasizes the integration between BIM and MIVES, thus providing a reliable tool for all stakeholders in the project. The methodology incorporates two modules: (1) BIM module and (2) MIVES module. These modules are linked to one or more databases that contain the information necessary for sustainability analysis. To develop this methodology, Autodesk Revit software and Microsoft Excel have been used.

The successful implementation of the methodology represents a significant advance in the ability to achieve sustainable development in viaduct projects, evaluate their impacts and obtain a project sustainability index.

The following sections present the proposed methodology and an academic exercise to illustrate the methodology.

3.2 Methodology

The objective is to propose a methodology that allows and facilitates the evaluation of sustainability. In order to attain this goal, the following stages must be carried out:

1 **Analysis of the viaduct project.** It is the first stage of the process. It consists of analyzing and studying the documents and information about the project. The analysis carried out allows defining the problem and determining the limits of the decision system. This stage is decisive since it is decided that it will be analyzed if the whole project or part of it.

2 Decision framework. To define the decision framework, it is necessary to carry out the first stage of the MIVES methodology. At this stage, the decision-making tree is established, made up of requirements, criteria and indicators that consider economic, environmental and social sustainability. The decision-making tree is weighted by AHP. This stage refers to what has already been defined in sections 2.3 and 2.3.1 of this work. The indicators defined will be subsequently used within stages three and four of this methodology.

3 BIM Modeling. In the BIM modeling stage, what is described in section 2.4 of this document is developed. This stage is the most important to couple the BIM and MIVES methodologies. In the modeling, the physical and functional characteristics of the project are virtually represented. These characteristics are defined in the project documents analyzed in phase 1 of this methodology. The indicators of the decision-making tree defined in the previous phase must be included in the model as customized parameters. Once the model has been built, a database has been generated with all the information on the objects that the model contains. This database includes the information of the parameters defined by default and the custom parameters that we have created. At the end of this stage, the data generated in the BIM model must be extracted and this is done by exporting the database to a .TXT file that can be read in a spreadsheet that contains the proposed MIVES methodology.

4 Values function. In this stage, the parameters that define the equation of the value function for each indicator are obtained. The procedure described in section 2.3.2 of this document is followed. It is important to emphasize that at this stage the information generated in the BIM model is imported. This information allows defining and adjusting the value functions in addition to establishing the measure of each indicator defined in stage 2.

5 Sustainability Index. The last stage of this methodology is to calculate the sustainability index of the project using equation 2.6 defined in section 2.3.3 of this work. For this, in stage 2, the weighted decision-making tree was defined and in stage 4, using information obtained from the BIM methodology applied in the MIVES methodology, the value function and the measure for each indicator were established. Additionally, scenarios are proposed in which the weighting made in stage 2 can be modified. This modification does not require the entire process to be carried out again since the weighting does not modify stages 3 and 4.

Figure 3.1 presents the flow diagram for the previously described methodology. The described methodology is structured in sequential order, however, it is not expected that the researchers always process in this way, they could carry out the activities in another order.

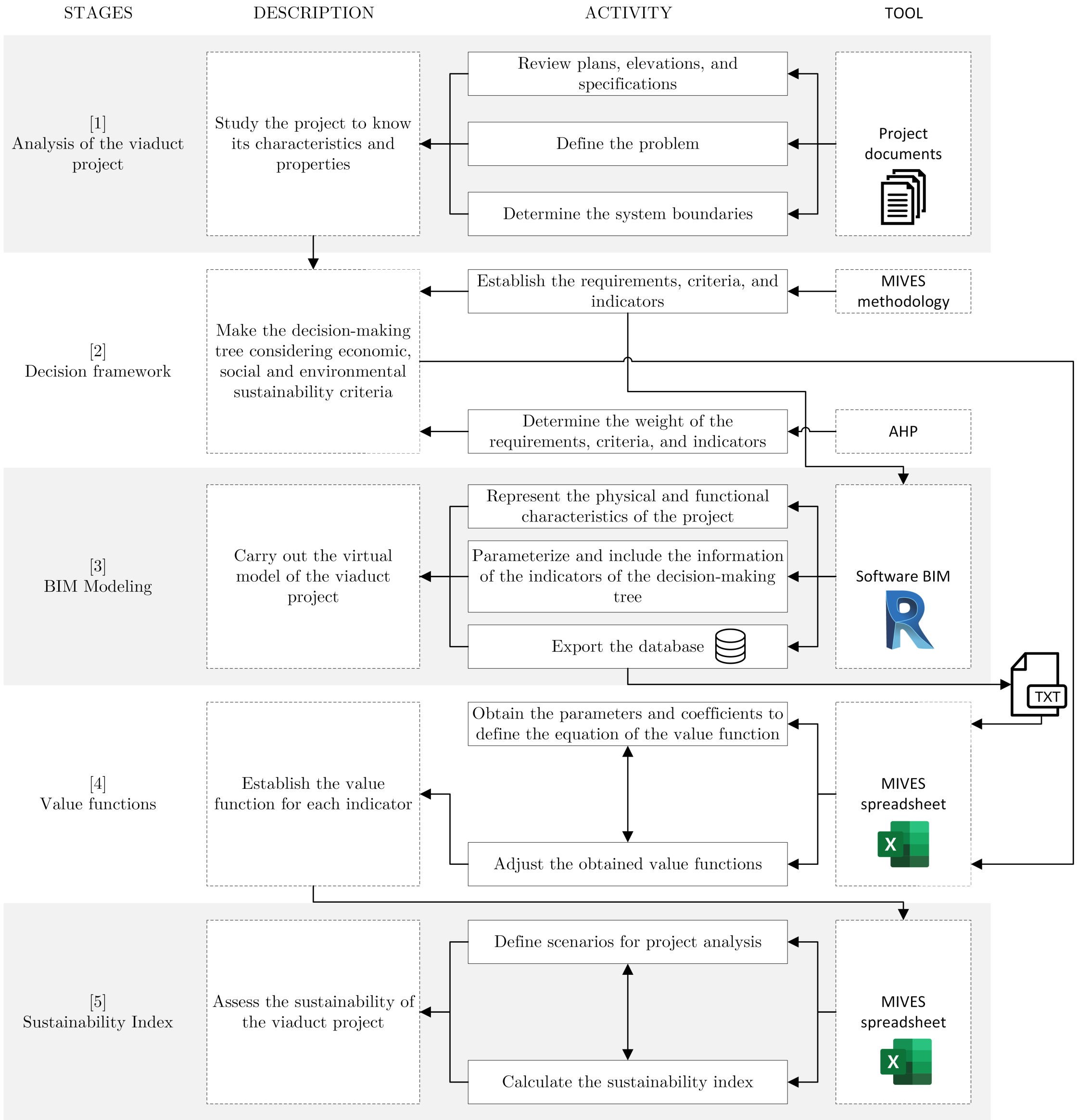


Figure 3.1: Flowchart of the new methodology for sustainability assessment in viaduct projects.

3.3 Academic Example

This academic example was developed to illustrate the methodology presented in the previous section. The characteristics of the viaduct (figure 3.2 presented in this section are not relevant. Type sections defined in other similar projects have been considered.

1 **Analysis of the viaduct project.** For this academic example, the entire viaduct will be analyzed. All sections are considered as concrete structural material and it is of interest to evaluate the total cost.

2 **Decision framework.** The total cost has been taken as the only indicator with a weight of 23.10% within the decision-making tree.

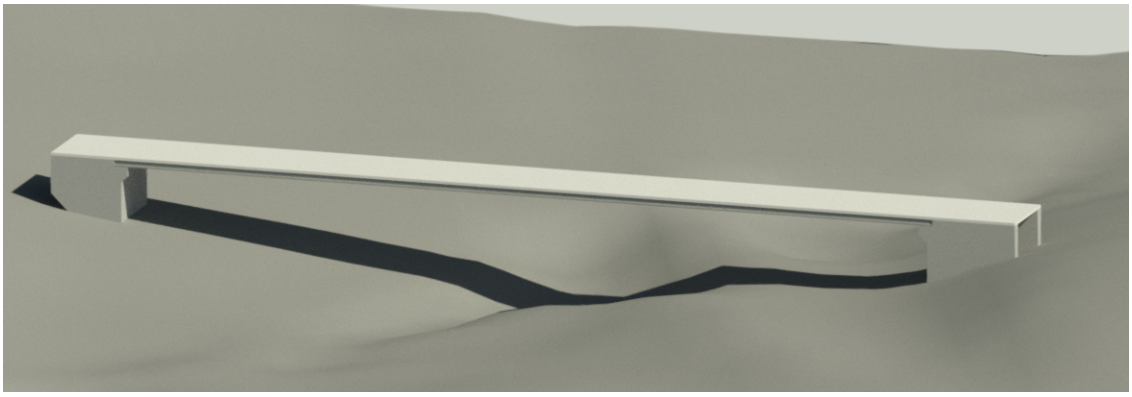


Figure 3.2: 3D view of the test viaduct.

3 BIM Modeling. Autodesk Revit software with a student license has been used to model this academic example. This software has been chosen because it is the dominant one in the BIM methodology and it is part of the BIM Autodesk family that allows the interaction between different programs. The model can be exported to .IFC format which allows the use of the information in more BIM platforms.

The necessary information is included in the model through parameters, these parameters can be defined as shared parameters (figure 3.3) for use in different models or as project-only parameters (figure 3.4).

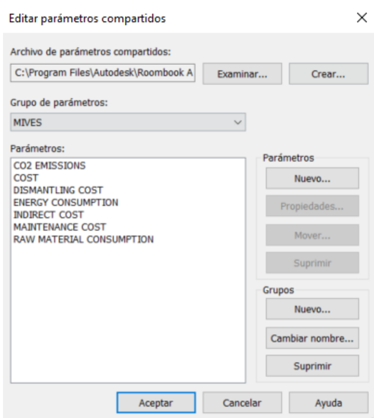


Figure 3.3: Shared parameters.

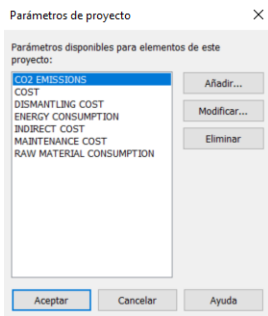


Figure 3.4: Project parameters.

Each parameter has properties that are configured according to the type of information entered. The properties even let choose which objects this information is added to. Figure 3.5 indicates the parameter properties window.

The information entered must be quantifiable and assignable to each object. The data for each parameter is assigned using the parameters for each material included in the material properties. Materials are defined based on project requirements. Figure 3.6 indicates the data entered for the concrete into the virtual model of the test viaduct.

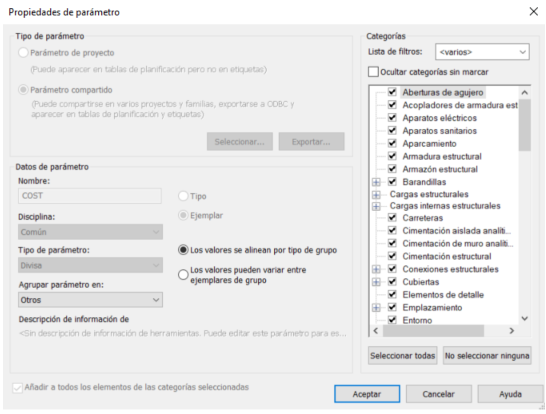


Figure 3.5: Parameter properties.

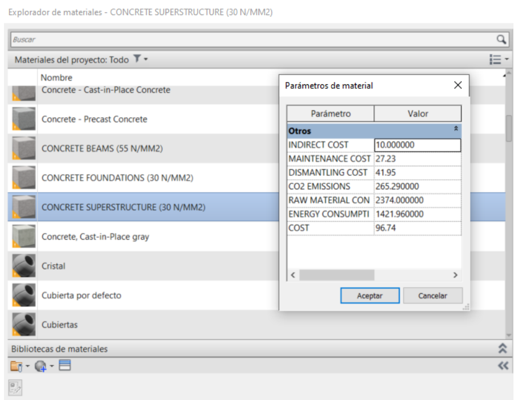


Figure 3.6: Material properties.

The material calculation properties window (figure 3.7) allows to customize the information that will be presented in the material quantity table. The information to apply the MIVES methodology is utilized. Numerical operations are allowed between the data to adapt the information to different needs. For the test model, the cost has been used and the academic example field has been created, which is the multiplication of the cost by the volume of the material.

The planning/quantities table (figure 3.8) presents the previously selected information. This information is the one that will be used for the sustainability evaluation using the MIVES methodology. The data in this table must be exported to a spreadsheet, which is done by generating a text file. This file is automatically generated by the program using the table report generation option. Figure 3.9 presents the report generated in a spreadsheet.

It is important to maintain order in the presentation of the information since the spreadsheet will be programmed to read the data in a determined way. At this point, the BIM methodology ends. Henceforth, the information obtained will be used to apply the MIVES methodology, the evaluation is carried out using a spreadsheet. If changes are made to the virtual model such as materials, dimensions, shapes, it will be reflected in the planning/quantification tables and they must be exported again to update the information in the spreadsheet.

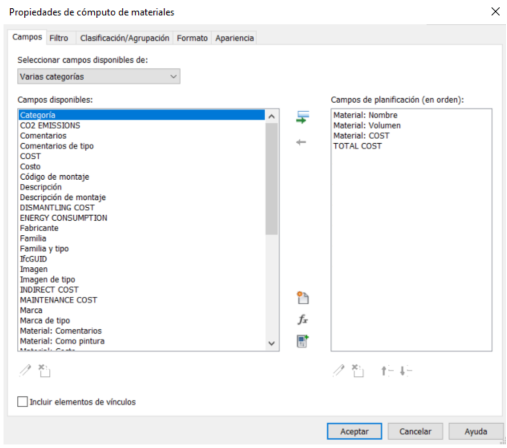


Figure 3.7: Materials schedule/quantities properties.

MATERIALS QUANTITIES

<MATERIALS QUANTITIES>			
A	B	C	D
MATERIAL: NAME	MATERIAL: VOLUME	MATERIAL: COST	TOTAL COST
CONCRETE- 35 MPa	126.60 m³	96.74	12247.23

Figure 3.8: Materials schedule - quantities.

Column1	Column2	Column3	Column4
MATERIALS QUANTITIES			
MATERIAL: NAME	MATERIAL: VOLUME	MATERIAL: COST	TOTAL COST
CONCRETE- 35 MPa	126.60	96.74	12247.23

Figure 3.9: Materials schedule - quantities report.

4 **Values function.** The value function (figure 3.10) has been obtained and adjusted based on the information exported from the BIM model and processed using a spreadsheet. Shape and limits of function have been imposed.

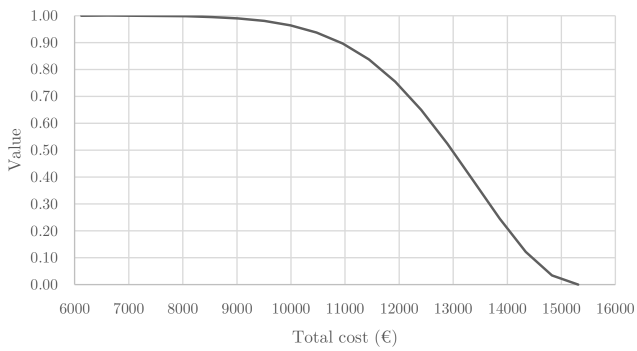


Figure 3.10: Materials schedule/quantitiessad properties.

5 **Sustainability Index.** The calculation of the sustainability index has been carried out with the imposed weight of 23.10%, the value function obtained in the previous phase and the measurement of the total cost presented in figure 3.9. The value obtained corresponds to the sustainability index for the total cost, however, this value is not presented so as not to divert attention from the case study presented in the next chapter.

Chapter 4

Case Study "Las Arenas Viaduct"

4.1 General description

The case study consists on the analysis of a viaduct called "Las Arenas Viaduct", which is 128 m long and is composed by 4 spans with a maximum distance between supports of 33 m, a slab 15 m. wide, 3 central piles with pier cap that support double T beams prefabricated and prestressed (figure 4.2).

The foundations are deep and include pile walls and individual piles. This viaduct is in the final stage of the project, since studies and designs have been completed, it is ready for construction. It will be part of the C-58 road between Sabadell and Terrassa, Spain crossing the "De las Arenas" stream (figure 4.1). The complete C-58 highway expansion project will save drivers around 200000 hours a year and 215 tons of CO_2 emissions. The project is promoted by the government of Catalonia and is currently in the execution stage.

The objective of this chapter is to apply the methodology presented in the previous chapter to the described viaduct. It is important to highlight that the original analyses of this structure did not contemplate a virtual model of the project therefore, it will be done as part of this thesis.

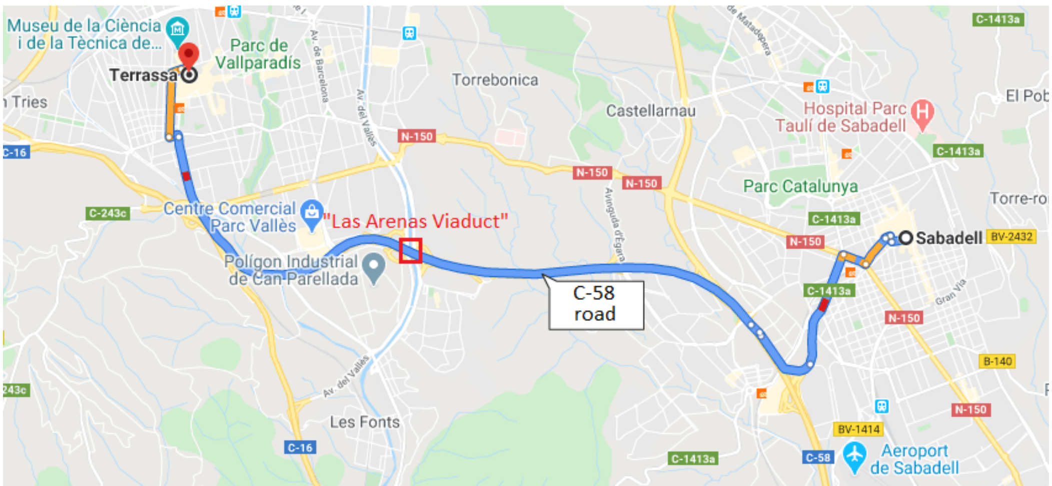


Figure 4.1: General view of the C-58 road and the location site of the "Las Arenas Viaduct" (Google Maps).

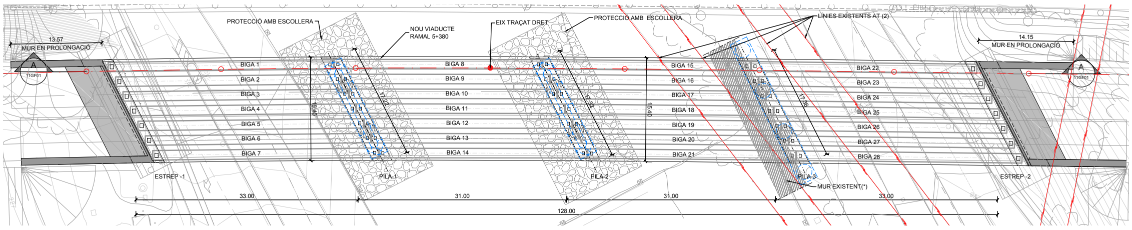


Figure 4.2: “Las Arenas Viaduct” plan view (dimensions in meters).

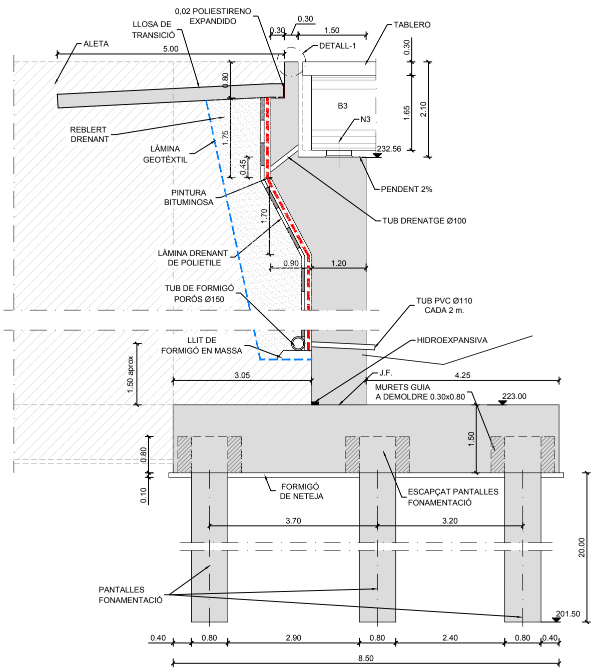


Figure 4.3: Abutment cross-section.

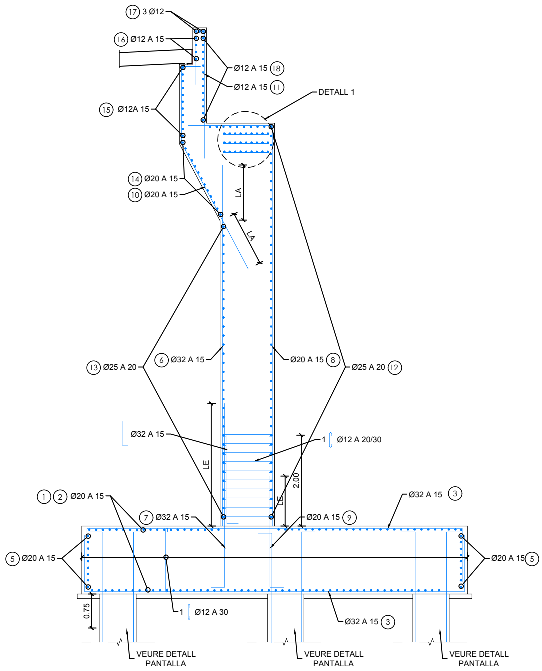


Figure 4.4: Abutment reinforcement details.

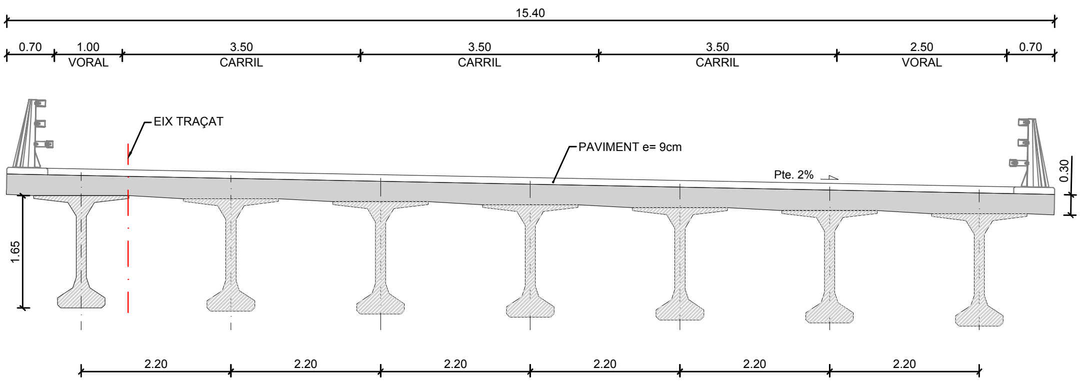


Figure 4.5: Beams and slab cross-section (dimensions in meters).

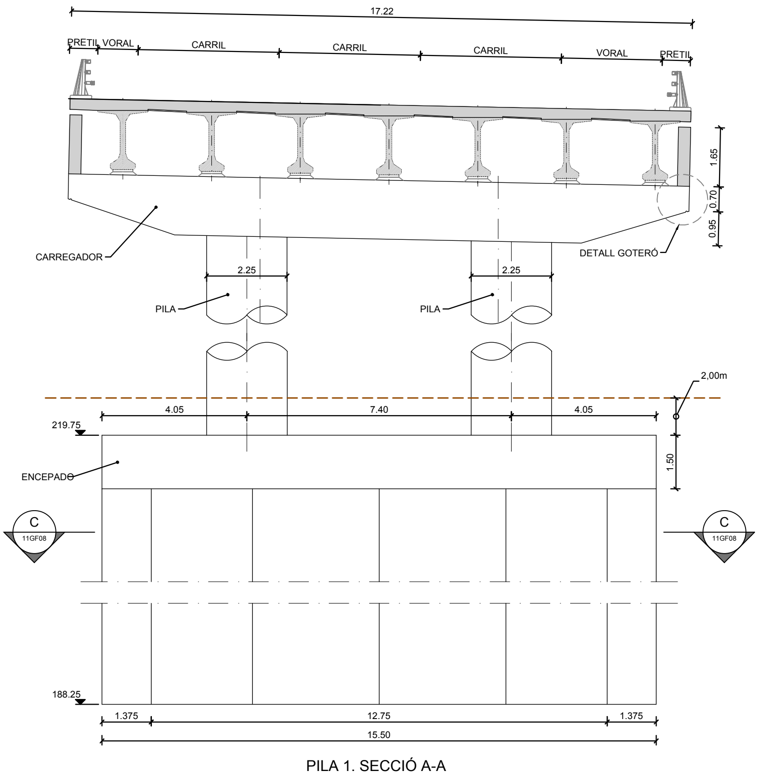


Figure 4.6: Foundation, piles and header cross-section (dimensions in meters).

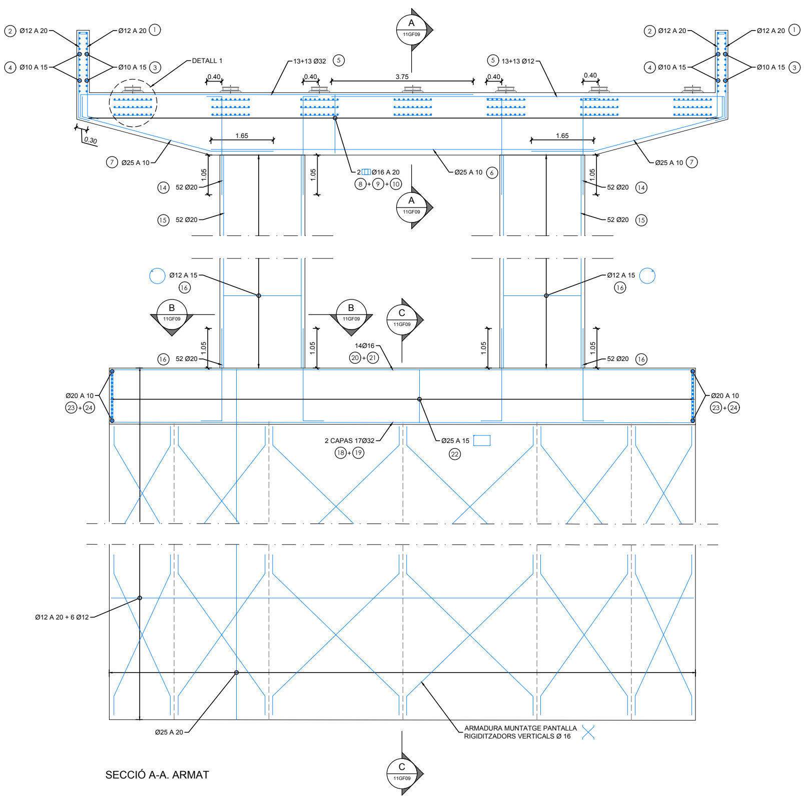


Figure 4.7: Foundation, piles and header reinforcement details.

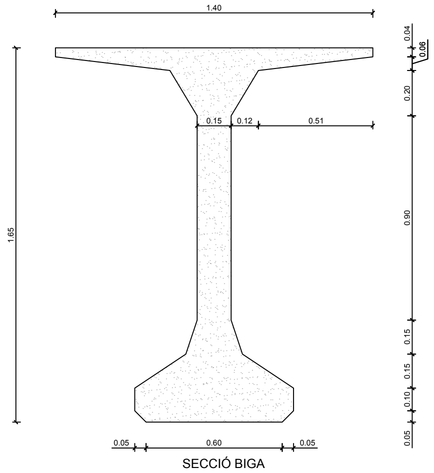


Figure 4.8: Beam cross-section.

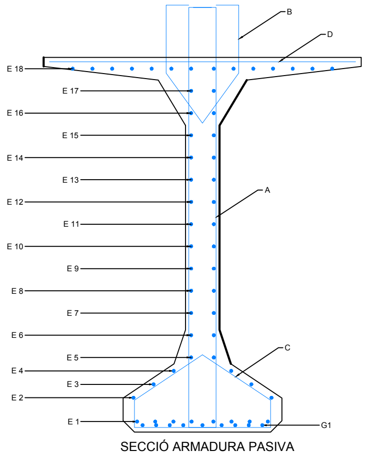


Figure 4.9: Beam reinforcement description.

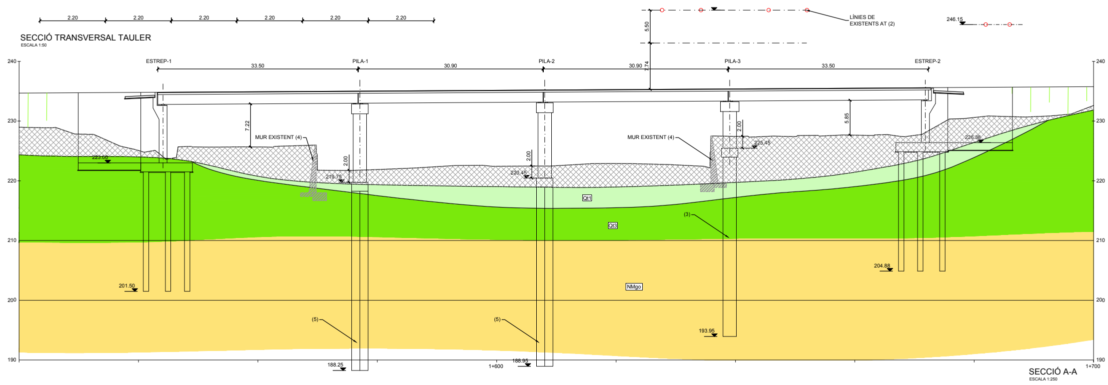


Figure 4.10: “Las Arenas Viaduct”, frontal view elevation.

4.2 BIM modeling

Modeling is the action of virtually representing physical and functional characteristics using computer tools. The virtual model contains objects that through parameters contain information that can be used according to requests in different applications.

The virtual model was carried out based on information from the project (plans, elevations and specifications) (figure 4.10) that is the property of the Government of Catalonia. The topography of the terrain was developed using a Geographic Information System (GIS) with data from the Cartographic and Geological Institute of Catalonia (ICGC). The topography obtained was exported from GIS and included in BIM as a surface.

The modeling has been carried out on the viaduct superstructure (foundations, walls, pillars, beams, and slabs). Functional details have been omitted.

Figures 4.11, 4.12 and 4.13 indicate the front and 3D views respectively of the virtual model of the “Las Arenas Viaduct”. The model consists of objects that represent each of the elements and characteristics indicated in the project plans. The topography has been integrated and allows interaction between the superstructure and the natural terrain.

Figure 4.11: “Las Arenas Viaduct” virtual model, frontal view elevation.

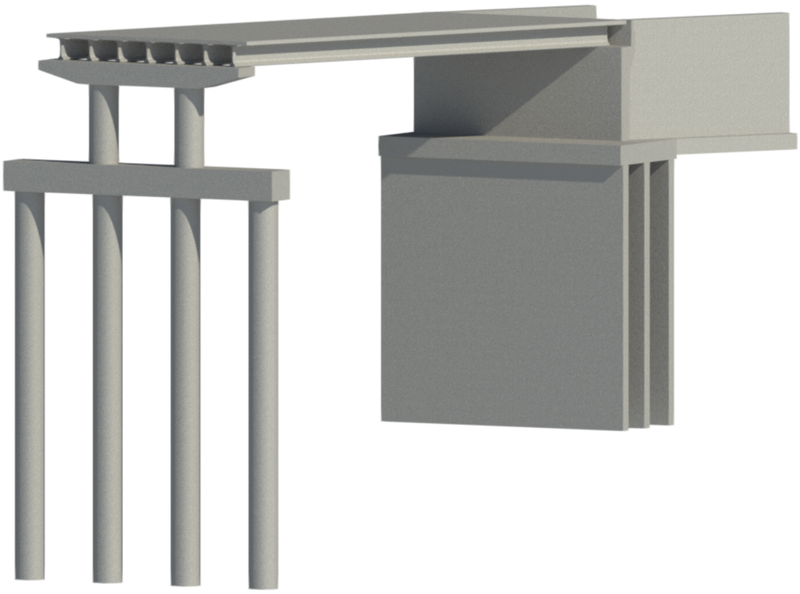


Figure 4.12: “Las Arenas Viaduct” virtual model, elements, 3D view.

Figure 4.13: “Las Arenas Viaduct” virtual model, 3D view.

According to the AIA classification a LOD 400 has been developed. Each element has detailed information on its location, elevation, orientation, material and structural classification. Linked to each object is the reinforcement that also contains the information described above. The model of this case study seeks to evaluate sustainability, therefore a high LOD has been defined. However, an analysis can be made about the influence of the level of development of the model on the sustainability index and determine if the variability is determining or not.

Figures 4.14 and 4.15 are samples of the BIM modeling of the structural sections and their reinforcement.

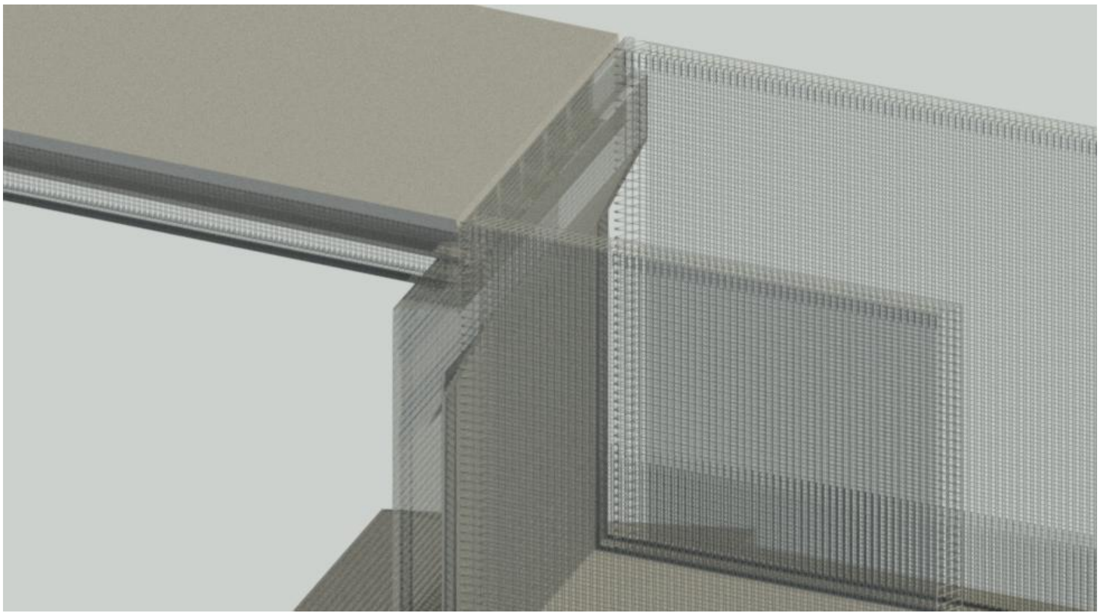


Figure 4.14: “Las Arenas Viaduct” virtual model, abutment, reinforcing bar detailing view.

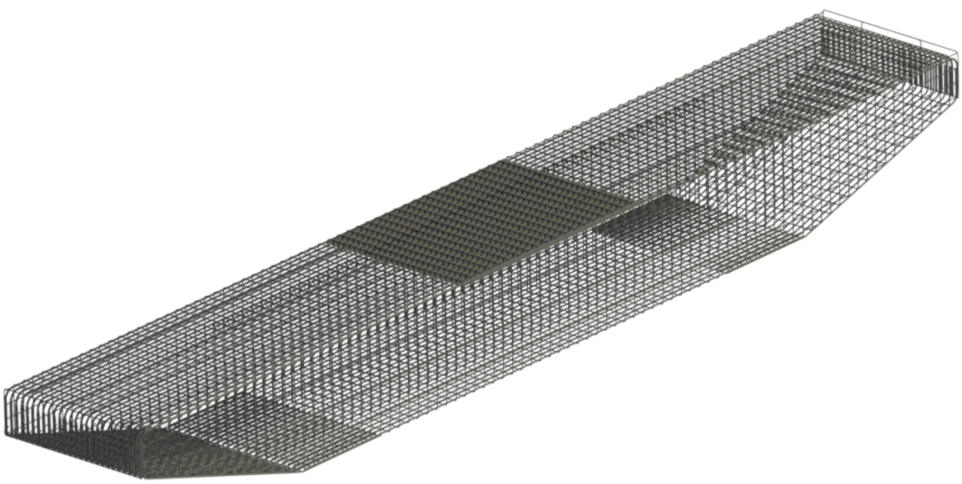
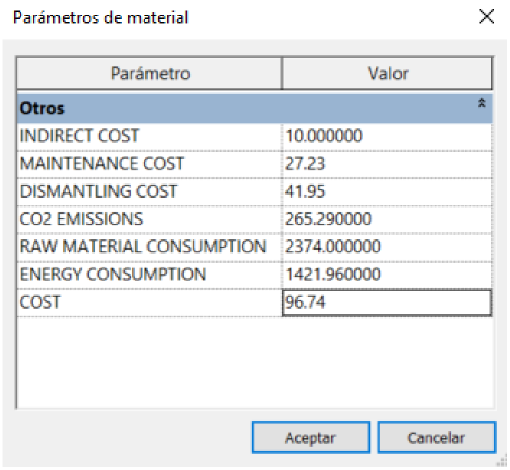


Figure 4.15: “Las Arenas Viaduct” virtual model, header beam, reinforcing bar detailing view.

Parametric modeling has been used to complement the information of each object. Although the LOD 400 contains information that defines the object, this section incorporates the information necessary for the subsequent sustainability assessment. The information entered in the form of parameters can be quantitative or qualitative. Quantitative information can be mathematically operated.



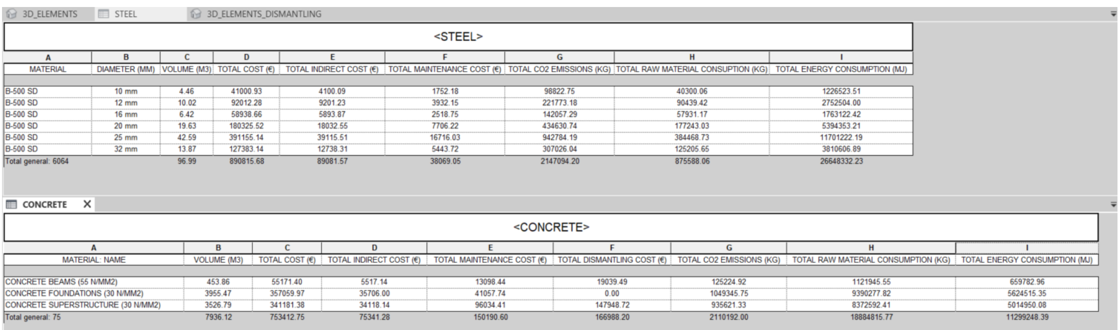
Parámetros de material

Parámetro	Valor
Otros	
INDIRECT COST	10.000000
MAINTENANCE COST	27.23
DISMANTLING COST	41.95
CO2 EMISSIONS	265.290000
RAW MATERIAL CONSUMPTION	2374.000000
ENERGY CONSUMPTION	1421.960000
COST	96.74

Figure 4.16: Parameters included in the BIM model. The values correspond to the concrete of the superstructure.

The information parameterized (figure 4.16 corresponds to the sustainability indicators defined in the section 4.3.2. The economic and environmental indicators are quantitative and can be assigned to each object in the model, however, the social indicators are qualitative and their application is global. Social indicators will not be part of the information parameterized in each object.

Figure 4.17 presents the database obtained from the BIM methodology based on the base and custom parameters used in the modeling. This database contains the economic and environmental information necessary to apply the MIVES methodology in the case study.



<STEEL>

A	B	C	D	E	F	G	H	I
MATERIAL	DIAMETER (MM)	VOLUME (M3)	TOTAL COST (€)	TOTAL INDIRECT COST (€)	TOTAL MAINTENANCE COST (€)	TOTAL CO2 EMISSIONS (KG)	TOTAL RAW MATERIAL CONSUPTION (KG)	TOTAL ENERGY CONSUMPTION (MJ)
B-500 SD	10 mm	4.46	41000.93	4100.09	1752.18	98822.75	40300.06	1226523.51
B-500 SD	12 mm	10.02	92012.28	9201.23	3932.15	221773.18	90439.42	2752504.00
B-500 SD	16 mm	6.42	58938.66	5893.87	2518.75	142057.29	57931.17	1763122.42
B-500 SD	20 mm	19.63	180325.52	18032.55	7706.22	434630.74	177243.03	5394353.21
B-500 SD	25 mm	42.59	391155.14	39115.51	16716.03	942784.19	384468.73	11701222.19
B-500 SD	32 mm	13.87	127383.14	12738.31	5443.72	307026.04	125205.65	3810606.89
Total general: 6064		96.99	890815.68	89081.57	38069.05	2147094.20	875588.06	26648332.23

<CONCRETE>

A	B	C	D	E	F	G	H	I
MATERIAL: NAME	VOLUME (M3)	TOTAL COST (€)	TOTAL INDIRECT COST (€)	TOTAL MAINTENANCE COST (€)	TOTAL DISMANTLING COST (€)	TOTAL CO2 EMISSIONS (KG)	TOTAL RAW MATERIAL CONSUMPTION (KG)	TOTAL ENERGY CONSUMPTION (MJ)
CONCRETE BEAMS (55 N/MM2)	453.86	55171.40	5517.14	13098.44	19039.49	125224.92	1121945.55	659782.96
CONCRETE FOUNDATIONS (30 N/MM2)	3955.47	357059.97	35706.00	41057.74	0.00	1049345.75	9390277.82	5624515.35
CONCRETE SUPERSTRUCTURE (30 N/MM2)	3526.79	341181.38	34118.14	96034.41	147948.72	935621.33	8372592.41	5014950.08
Total general: 75	7936.12	753412.75	75341.28	150190.60	166988.20	2110192.00	18884815.77	11299248.39

Figure 4.17: Economic and environmental data obtained from the BIM database.

4.3 MIVES application

The methodology for evaluating sustainability in the case study is defined using the theoretical basis of MIVES defined in section 2.3. The process to assess sustainability is divided into the following steps:

1 **Definition of the problem.** It consists of defining the boundary conditions and the limits, these define the circumstances presented and determine the system to be studied.

2 **Realization of the decision-making tree.** It includes the requirements, criteria and indicators that will be analyzed. These aspects must be independent and representative.

3 **Definitions of he mathematical functions.** Each indicator must be correctly expressed through a value function that allows quantifying and comparing the different indicators. The value function allows each indicator to be given a dimensionless value that represents the satisfaction.

4 **Definition of the weights to be assigned to each variables.** All the components of the decision-making tree must be characterized through the assignment of weights that represents the importance of each one.

5 **Calculate the sustainability index.** The index reflects the economic, environmental and social balance of the system.

In the following sections, the indicated steps are fully developed and justified.

4.3.1 System boundaries

Several factors influence the sustainability assessment of a viaduct. Thus, not all factors can be considered, limitations must be imposed on the system to be studied. The purpose of limitations is to ensure that the parameters considered are representative. The factors have been determined based on the base case study and its possible modifications throughout its life cycle.

Within the system, all solutions for the viaduct are considered to meet all technical aspects. The technical aspects are not part of the considerations of this evaluation. The requirements and indicators are defined considering the three main branches of sustainability (economic, environmental and social). The evaluation system considers only the superstructure of the viaduct (foundations, walls, pillars, beams and slabs).

4.3.2 Decision framework

In this section, the indicators that represent economic, environmental and social sustainability are defined. The evaluation of sustainability is defined in the construction of the decision-making tree. To guarantee and ensure the credibility of the results, each indicator must be consistent, objective and representative.

The decision-making tree can be defined based on seminars with experts from different sectors or through bibliographic review of previously carried out studies. The decision-making tree has been defined based on studies already carried out (Table 2.6) consistent with the current work. The assignment of weights to each component of the decision-making tree is based on a bibliographic review and is carried out by direct assignment. Eleven indicators have been defined that correspond to six criteria and three requirements.

Table 4.1 completely presents the decision-making tree with the weight assigned to each indicator, criteria and requirement.

Table 4.1: MIVES decision-making tree for the case study.

Requirement	α_i	**Criteria**	β_i	**Indicator**	γ_i
R1. Economic	55%	C1. Cost	50%	I1. Total cost	60%
				I2. Indirect cost	10%
				I3. Maintenance cost	20%
				I4. Dismantling cost	10%
		C2. Time	30%	I5. Ececution time	100%
R2. Environmental	25%	C3. Emissions	60%	I6. CO_2 emissions	100%
		C4. Resources	40%	I7. Raw material consumption	50%
				I8. Energy consumption	50%
R3. Social	20%	C5. Social indixes	40%	I9. Affected area	40%
				I10. General disturbances	60%
		C6. Safety	60%	I11. Health and safety during construction	100%

4.3.3 Definition of the indicators

All the indicators taken into account are described below. Its complete description allows a correct quantification. The data for each indicator has been obtained from the virtual model made with the BIM methodology. This section seeks to develop the indicators and justify their use.

The complete development of the indicators allows establishing the value functions for each one of them. The case study is presented as a reference to determine the value functions. The limits of the value function have been designated based on percentage variations of the value obtained from the case study. The section 4.3.4 compiles the functions of each indicator and presents the deparameters and coefficients considered.

R1. Economic requirements

This requirement aims to collect and classify economic indicators. Cost is quantified as a direct economic criterion and time as an influential criterion on cost. Within the economic requirement, there are four indicators that are fully described and developed below.

I1. Total cost

The total cost has been assumed from the base cost determined for this project by the government of Catalonia. From this base cost, the partial costs necessary for this study have been obtained. The total cost refers to the final price of the product obtained, taking into account labor, material, machinery, equipment and tools.

The total cost has been quantified in euros per square meter of slab. This unit of measurement has been used since it is common to compare projects based on this unit. Section A.1 presents the data obtained from the BIM model to obtain the total cost.

Undoubtedly, the total cost depends on the construction typology, the proposed structural solutions and the materials chosen for the project. The maximum and minimum limits are obtained based on the total cost of the project presented by the government of Catalonia. To determine the maximum limit, an extra 25% of cost with respect to the base cost has been determined as unacceptable. As a minimum limit and that would provide the greatest satisfaction, a 50% decrease of the base cost is considered.

Figure 4.18 shows the value function of the total cost, expressed in euros per square meter of slab.

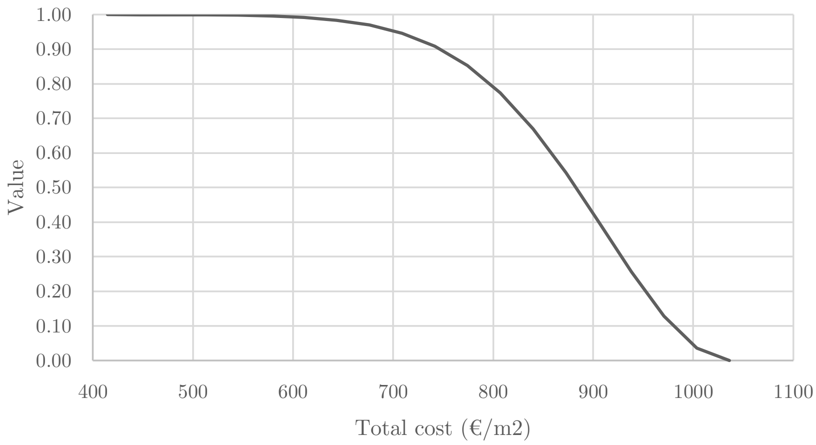


Figure 4.18: Value function for total cost (I1).

The cost function is represented by a decreasing S-shape function. It is clear that the lower the total cost, the greater the satisfaction.

I2. Indirect cost

Indirect cost is defined as a percentage that cannot be directly related to the work performed. Indirect cost includes costs for operations, financing, construction systems, tests and controls, contingencies, insurance, company expenses, etc.

All these associated costs cannot be related to the activities carried out but can be related to the duration of the entire project. Commonly the indirect cost represents between 5-20% of the total cost. The project presented by the government of Catalonia defines an indirect cost of 10%. Despite indirect cost can be directly related to direct cost, this is not the case because although it is calculated from direct cost, the percentage depends on the associated costs described above. Section A.1 presents the data obtained from the BIM model.

Figure 4.19 indicates the value of the indirect cost function expressed in euros per square meter of slab.

The higher the indirect cost, the less satisfaction. This entails a decreasing convex value function.

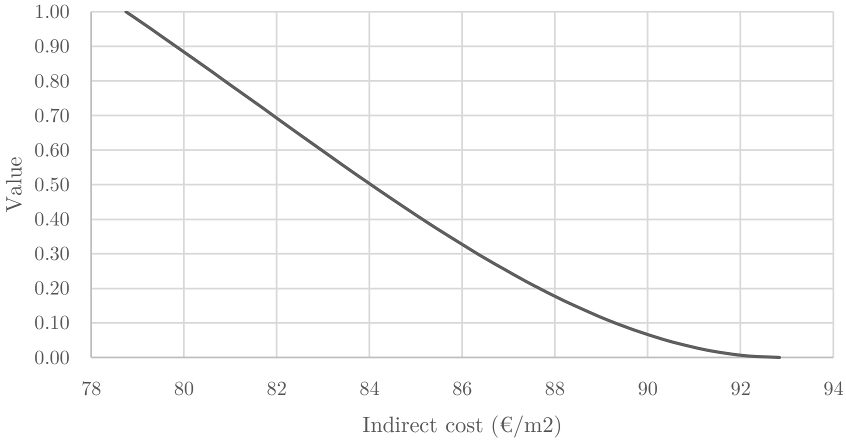


Figure 4.19: Value function for indirect cost (I2).

I3. Maintenance cost

The maintenance cost includes the cost of the actions or operations necessary to keep an item in a specific state. Administrative costs, labor, spare materials and their storage, equipment rental, energy consumption, etc. are part of the maintenance cost. The maintenance cost is related to the materials and structural typology used in the project.

The maintenance cost for the materials used in the viaduct superstructure has been obtained from the construction price generator in Spain "CYPE Ingenieros". The maintenance cost for the first 10 years of useful life has been determined. Appendix A.1 presents the information obtained from the BIM model for the maintenance cost.

For the value function, the value of the maintenance cost of the case study has been taken as a reference, the limits of the function have been determined based on a percentage variation. A decrease of 25% and an increase of 50%.

Figure 4.20 presents the value function for the maintenance cost expressed in euros per square meter of slab.

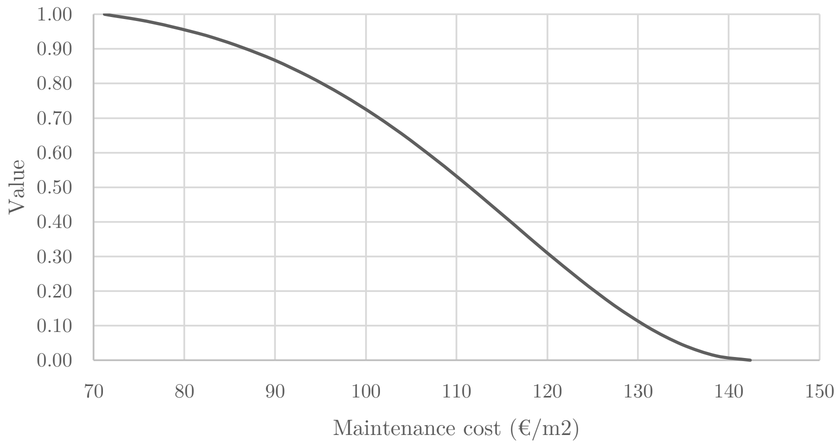


Figure 4.20: Value function for maintenance cost (I3).

The value function for maintenance cost it is a decreasing S-shape. When the maintenance cost increases, satisfaction decreases.

I4. Dismantling cost

The dismantling cost refers to the costs generated by the demolition and deconstruction of the structure. The dismantling techniques are several but are commonly done mechanically. The technique chosen for each structure depends on the typology, its location, its materials, etc.

The aim is to make the structures more and more suitable for deconstruction rather than demolition. Deconstruction minimizes environmental and social impacts. In the case of study due to the structural typology and the materials used, a dismantling has been considered, the resulting material is intended to be used as recycled material in future projects. The dismantling cost has been obtained from the database of the Institute of "Construction Technology of Catalonia" (ITEC). The dismantling cost takes into account the steel included within the concrete. The foundations is not taken into account, figure A.7 indicates the structural parts considered.

The dismantling cost for the case study has been determined as a reference to establish the maximum and minimum limits of the value function. A maximum increase of 25% and a decrease of 40% have been considered. Appendix A.1 presents the information obtained from the BIM model for the maintenance cost.

Figure 4.21 indicates the value function for the dismantling cost expressed in euros per square meter of slab.

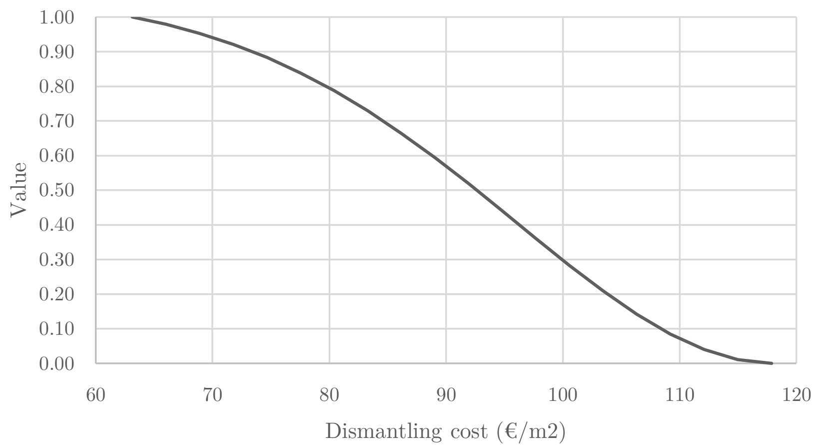


Figure 4.21: Value function for dismantling cost (I4).

The value function for dismantling cost it is a decreasing S-shape. When the dismantling cost increases, satisfaction decreases.

I5. Execution time

The execution time encompasses the time necessary for each of the activities contemplated in the project execution plan to be carried out. In this case, the activities will be those necessary to complete the superstructure of the viaduct.

The case study does not have an execution plan so its development is part of this work. The project execution plan has been carried out adjusting the time to the term required by the government of Catalonia. Figure A.9 of Appendix A.1 presents the execution plan for the case study.

The execution time of the case study has been taken as a reference to establish the upper and lower limits of the value function. A variation of 50% and 20% respectively have been considered for the maximum and minimum execution time.

Figure 4.22 indicates the value function for the execution time expressed in days.

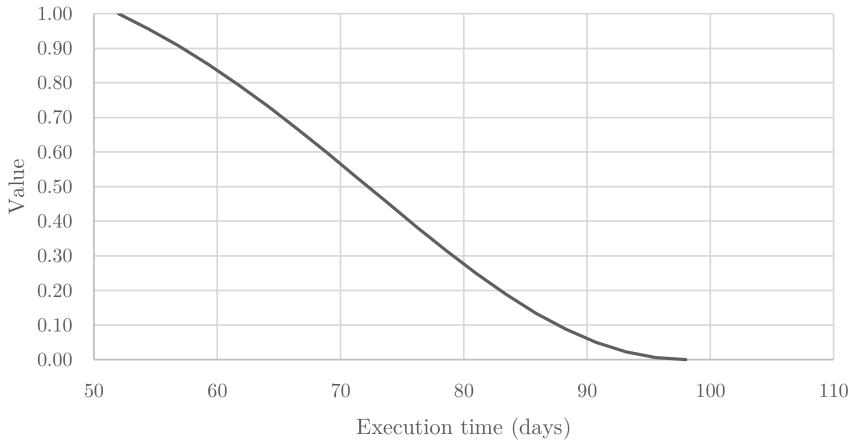


Figure 4.22: Value function for execution time (I5).

The value function is a decreasing S-shape. The change in execution time is reflected in a gradual change in the satisfaction value.

R2. Environmental requirements

The environmental requirement aims to quantify and compare the most important environmental impacts. The AEC industry carries many environmental impacts, however, it is not convenient to have a large number of indicators, therefore they are considered the most representative. The three environmental indicators considered are fully developed below.

To determine the maximum and minimum limits of the function value, the case study was considered as a reference. The limits are defined with a 25% increase and decrease.

I6. CO_2 Emissions

CO_2 emissions encompass the emission of pollutants generated by the materials of the structure. The emission of carbon dioxide has been determined as the representative of the emissions due to its ease of calculation and the importance within climate change.

The materials considered are concrete and steel, which emit the most pollutants. The data for the quantification of emissions has been obtained from the database of the Institute of "Construction Technology of Catalonia" (ITEC). The information has been considered within the parameters of the BIM model. Appendix A.2 presents the emissions generated in the case study.

Figure 4.23 indicates the value function for CO_2 emissions expressed in kilograms of carbon dioxide equivalent per square meter of slab.

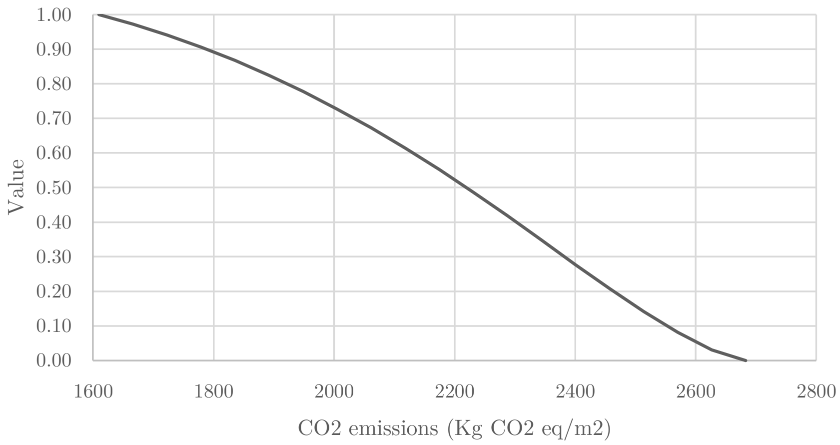


Figure 4.23: Value function for CO_2 emissions (I6).

The value function approximates a s-shape trend. The increase in emissions entails a drastic decrease in satisfaction.

I7. Raw material consumption

The consumption of raw material takes into account the amount of material necessary for the manufacture of construction materials. Raw material refers to matter extracted from nature and which may or may not be renewable. Quantifying the raw material consumed helps to establish the impact on the environment since overuse can cause depletion of the resources.

The data for the quantification of the raw consumption materials have been obtained from the database of the Institute of "Construction Technology of Catalonia" (ITEC). Appendix A.2 presents the quantity of raw material consumed in the case study.

Figure 4.24 indicates the value function for the consumption of raw material expressed in kilograms per square meter of slab.

The value function tends to a S-shape form. Excessive consumption of raw material is notoriously penalized.

I8. Energy consumption

Energy consumption refers to the energy required for the production of construction materials. The predominant materials in the case study are concrete and steel. The evaluation will focus on those materials.

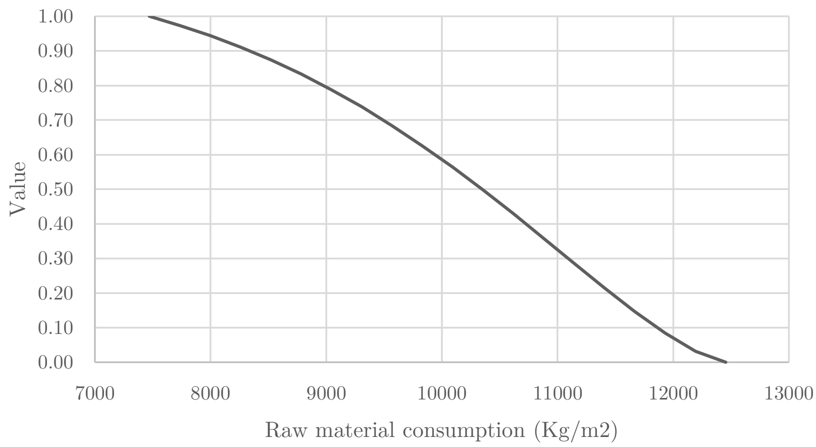


Figure 4.24: Value function for raw material consumption (I7).

The data for the quantification the energy consumption have been obtained from the database of the Institute of "Construction Technology of Catalonia" (ITEC). The amount of energy consumed in the case study is presented in Appendix A.2.

Figure 4.25 indicates the value function for energy consumption expressed in megajoules per square meter of slab.

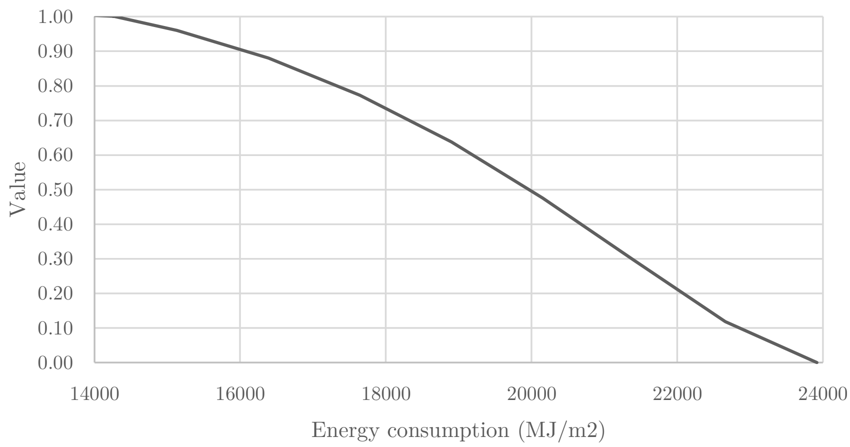


Figure 4.25: Value function for energy consumption (I8).

The value function for energy consumption has a S-shape form. The higher the energy consumption, the less satisfaction.

R3. Social requirements

The social requirement aims to analyze the impact and integration of the project within society. Three indicators grouped into two criteria have been determined, which are fully developed below. The social indicators have not been parameterized in the BIM model due to their qualitative and global nature. However, its evaluation is made based on general information obtained from the BIM model.

I9. Affected area

The affected area indicator seeks to represent the space needed to carry out the work. This space should normally be adequate for the work to be carried out. Depending on the structural typology, the materials and the project, this area will be larger or smaller.

The affected area has been determined according to the machinery used for the activities described in the project execution plan (figure A.9).This area will serve as the basis for defining the maximum and minimum limits of the value function with an increase and decrease of 20% and 50% respectively. Appendix A.3 shows a top view of the viaduct studied and its affectation area.

Figure 4.26 presents the value function obtained for the affected area expressed in square meters.

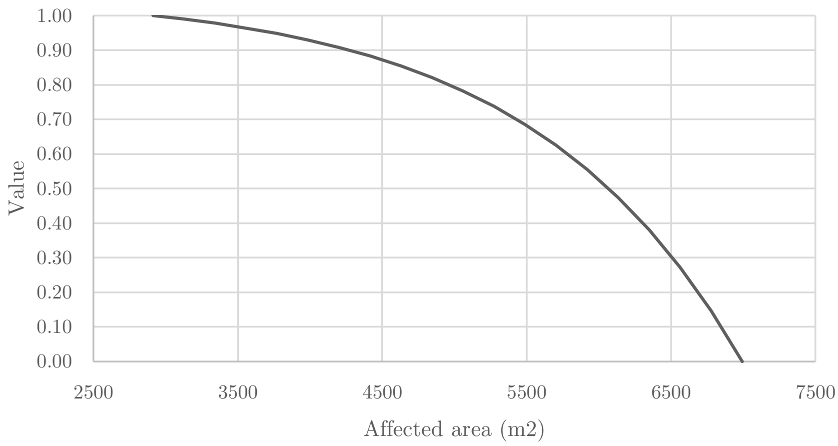


Figure 4.26: Value function for affected area (I9).

The value function is a decreasing concave shape since a greater area of affected leads to less satisfaction.

I10. General disturbances

The general disturbances encompass the social consequences of the project and assess the conditions generated around the surroundings by its execution. The development of this indicator is based on the evaluation of different types of disturbances generated to third parties by assigning weights and points [61, 55].

Three types of nuisance have been determined: noise, transit and traffic. The weight assigned to the disturbance depends directly on the type and location of the project. In the case of the study, noise is considered the most important disturbance due to the structural solutions adopted and the location of the project. Traffic has less weight since it is not a work that cuts or modifies traffic directly but rather causes discomfort at the entrance and exit of machinery. Similarly, with the transit of people, the location of the works downplays this disturbance.

The development of this indicator is found in Annex A.3. Table 1 indicates the discomfort considered with their respective weights and points. Table 2 provides the result of the evaluation of discomfort for the case study. The value function has as lower and upper limit of 0 and 10 points respectively.

Figure 4.27 presents the value function obtained for general disturbances expressed in points.

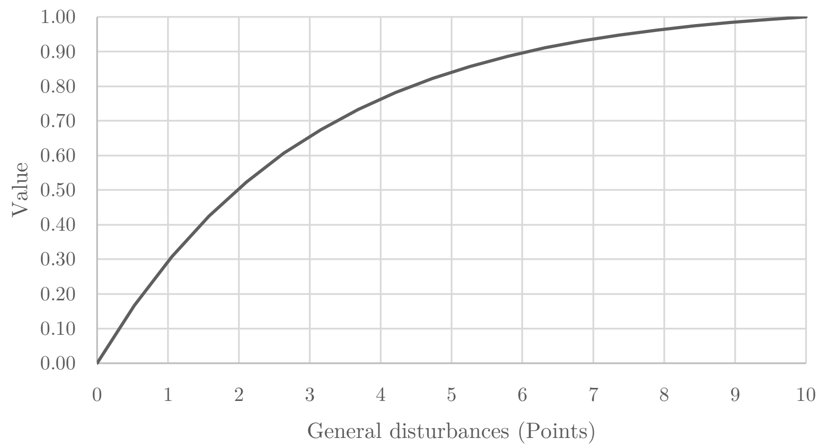


Figure 4.27: Value function for general disturbances (I10).

The value function is an increase concave shape since the reduction of discomfort points means greater satisfaction.

I11. Health and safety during construction

The evaluation of the safety and health index during construction was carried out with the “Occupational Risk Index” (ORI) [4]. The calculation is in Appendix A.3. Table A.3 presents the risks considered within the activities and the ORI calculation of each of the activities is presented in table A.4. The calculation has been made based on the project execution plan (figure A.9).

To determine the maximum and minimum limits of the function value, the case study was considered as a reference. The limits are defined with a 25% increase and decrease.

The figure 4.28 indicates the value function for the safety and health indicator during construction expressed by the ORI.

The shape of the value function is decreasing concave. A significant decrease in ORI represents a considerable improvement in satisfaction value.

4.3.4 Value functions

In section 4.3.3 each indicator has been developed obtaining the parameters and coefficients necessary to determine the value function (V_i) for each one. The value function transforms the units of each indicator into a dimensionless satisfaction value between 0 and 1. The transformation to a dimensionless unit allows to operate between indicators.

Figure 4.28: Value function for health and safety during construction (I11).

The indicators can be represented with decreasing (D) or increasing (I) functions, these being linear (Lr), concave (Ce), convex (Cx) or S-shaped (S).

Table 4.2 compiles the parameters and coefficients used for the value function corresponding to each indicator. The value function has been defined by the equation 2.4 indicated in section 2.3.2 of this document.

Table 4.2: Parameters and coefficients for each indicator value function (V_i).

Indicator	Unit	P_{max}	P_{min}	n_i	m_i	A_i	K_i	P_i	V_i	Shape
I.1 Total cost	€/m_2	1036.18	414.47	625.00	10	1.90	1.00	828.94	0.707	S-D
I.2 Indirect cost	%	92.84	78.75	80.00	20	1.90	1.92	82.89	0.607	Cx-D
I.3 Maintenance cost	€/m_2	142.37	71.18	130.00	10	1.90	1.04	94.91	0.804	S-D
I.4 Dismantling cost	€/m_2	117.86	63.14	75.00	5	1.90	1.07	84.19	0.710	Cx-D
I.5 Execution time	days	98.00	52.00	160.00	20	2.00	1.24	65.00	0.709	S-D
I.6 CO_2 Emissions	Kg CO_2eq/m_2	2682.91	1609.75	1500.00	3	1.45	1.19	2146.33	0.583	S-D
I.7 Raw material consumption	Kg/m_2	12452.86	7471.72	12000.00	7	1.45	1.16	9962.29	0.596	S-D
I.8 Energy consumption	MJ/m_2	23914.29	14348.57	15000.00	4	1.45	1.14	19131.43	0.609	S-D
I.9 Affected area	m_2	6991.88	2913.29	5826.57	4	1.00	1.06	5826.57	0.568	Ce-D
I.10 General disturbances	Points	0.00	10.00	3.00	1	1.00	1.04	3.40	0.703	Ce-I
I.11 Health and safety during construction	ORI	1485.64	891.39	1000.00	3	1.00	1.20	1188.51	0.709	Ce-D

The value functions and parameters defined in this work can be taken as a reference; however, these can be adapted according to the preferences of the stakeholders involved in the decision procedure for the evaluation of other viaduct projects.

4.4 Sustainability Index

This section develops the last part of the MIVES methodology. It consists of calculating the hierarchical level of the decision-making tree until reaching the global sustainability index.

Once the value function has been defined for each indicator, the value of the sustainability index for the viaduct can be calculated. The sustainability index (S.I) is calculated with equation 2.6 presented in section 2.3.3. This is described as the weighted sum of all the indicators analyzed. The weighting is performed according to each indicator, criteria and requirement defined in table 4.1 in section 4.3.2.

Table 4.3 presents three sustainability indexes S.I$_1$, S.I$_2$ and S.I$_3$ obtained for the case study. S.I$_1$ index has been calculated based on the weights assigned in the decision-making tree defined in section 2 of this work. However, these weights may be debatable during a period of economic crisis or under the concept of balanced sustainability. To consider these cases, two additional scenarios S.I$_2$ and S.I$_3$ have been considered. The purpose of having three scenarios is to verify the solidity of the sustainability score obtained, as well as the flexibility of the proposed model in relation to the ability to fulfill different interests of the various stakeholders. S.I$_2$ considers the concept of sustainability balanced, thus the weight of each requirement α(R1) = α(R2) = α(R3) = 33%. S.I$_3$ covers the economic crisis scenario, thus the weight of each requirement α(R1) = 75%, α(R2) = 10% and α(R3) = 15%. This scenario considers the economic requirement as more important and leaves out the environmental and social aspects. It should be noted that these weights would be inadequate with respect to sustainability since social and environmental requirements are treated as secondary. However, this scenario could reflect the investor economic preference

Table 4.3: Assessment of the sustainability index for the case study.

Indicator	$[\alpha_i\beta_i\gamma_i]_1$	**S.I$_1$**	$[\alpha_i\beta_i\gamma_i]_2$	**S.I$_2$**	$[\alpha_i\beta_i\gamma_i]_3$	**S.I$_3$**
I.1 Total cost	23.100%	0.163	14.00%	0.099	31.500%	0.223
I.2 Indirect cost	3.850%	0.023	2.333%	0.014	5.250%	0.032
I.3 Maintenance cost	7.700%	0.062	4.667%	0.038	10.500%	0.084
I.4 Dismantling cost	3.850%	0.027	2.333%	0.017	5.250%	0.037
I.5 Execution time	16.500%	0.116	10.000%	0.071	22.50%	0.159
I.6 CO_2 Emissions	15.000%	0.087	20.000%	0.117	6.000%	0.035
I.7 Raw material consumption	5.000%	0.030	6.667%	0.040	2.000%	0.012
I.8 Energy consumption	5.000%	0.030	6.667%	0.041	2.000%	0.012
I.9 Affected area	3.200%	0.019	5.333%	0.031	2.400%	0.014
I.10 General disturbances	4.800%	0.034	8.000%	0.056	3.600%	0.025
I.11 Health and safety during construction	12.000%	0.085	20.000%	0.142	9.000%	0.064
	100%	**0.678**	**100%**	**0.664**	**100%**	**0.698**

The general sustainability indexes obtained for each of the scenarios were S.I$_1$ = 0.678, S.I$_2$ = 0.664, S.I$_3$ = 0.698. It can be noticed that these indexes are very similar, this reflects the strength of the evaluation methodology proposed for the different scenarios analyzed. Additionally, these results confirm that viaduct projects have a slightly higher sustainability index in scenarios where the economic aspect is more important. This occurs because the environmental and social impacts of the construction of viaducts are not minor. Total cost, execution time, CO_2 emissions and safety and health during construction can be identified as the most important indicators within the sustainability index.

Beyond the results of the sustainability assessment in its different scenarios, it is important to highlight the new proposed methodology for analyzing viaduct projects and its versatility to adapt to the interests of decision-makers.

Chapter 5

Conclusions and Future Work

5.1 Conclusions

This work has focused on proposing a new methodology for evaluating sustainability in viaducts. No methodologies that integrate BIM and MIVES for the evaluation of sustainability could be found in the literature. To address the stated objective, first, the different methodologies for evaluating sustainability that considers economic, social and environmental aspects were reviewed. In addition, the BIM methodology was studied to know its qualities and functions. A new methodology for the evaluation of sustainability in viaducts that integrates BIM and MIVES was presented. This methodology is developed based on the need for correct and complete information to assess sustainability. The BIM methodology contributes as the information manager and MIVES analyzes it.

The developed methodology can be used to assess sustainability in different viaduct projects. The decision-making tree has been defined with 11 indicators that represent the main economic (R_1), environmental (R_2) and social (R_3) requirements. Three scenarios have been defined for the weights of the requirements $\alpha(R_i)$, criteria $\beta(C_i)$ and indicators $\gamma(I_i)$. Weights indicate the relative importance of each element of the decision-making tree and these can be calibrated to simulate different analysis conditions. In the same way, the defined value functions serve as a reference for future projects but can be adapted based on the decision-makers criteria. And BIM modeling can be developed in any type of project. These conditions allow the proposed methodology to be adaptable to different needs or particularities. It is intuited that the proposed methodology represents an improvement in the time that the sustainability evaluation takes. The improvement is generated by directly including the information from the virtual model in the MIVES methodology. However, this time improvement has not been quantified.

The developed methodology was applied to an academic example to verify the process and to the case study for validation. The results of the sustainability value for the case study were obtained. These results have been analyzed in order to characterize the solution and determine possible improvements to the project.

- Considering the first sustainability scenario with $\alpha(R_1) = 55\%$, $\alpha(R_2) = 25\%$ and $\alpha(R_3) = 20\%$, which represents the point of view of the investment part of the project, an index $\text{S.I}_1 = 0.678$ is obtained. On the other hand, when considering a sustainability balanced scenario with $\alpha(R_1) = \alpha(R_2) = \alpha(R_3) = 33\%$, the index obtained is $S.I_2 = 0.664$. Finally, when considering the economic crisis scenario with $\alpha(R_1) = 75\%$, $\alpha(R_2) = 10\%$ and $\alpha(R_3) = 15\%$, satisfaction reaches a value $S.I_3 = 0.698$.

- Note that there is no great difference between the values obtained from each scenario. This indicates that the project as it is being studied is quite optimal. The sustainability values obtained are good, but they do not come close to maximum satisfaction. It is concluded that the current solution of the case study is robust, however, improvements can be made to obtain a higher sustainability index.

- Total cost, CO_2 emissions, and safety and health during construction are the most important indicators of each requirement. The improvements that can be made to the project would be clearly reflected in these indicators. Thus, the 10% decrease in the measurement of each of the indicators would reflect an average increase of 12.56% in the value of the sustainability index. The satisfaction of each scenario would be $S.I_1 = 0.772$, $S.I_2 = 0.763$ and $S.I_3 = 0.760$. These improvements can be achieved by considering different structural materials, construction systems or dimensions. The optimization of the project should be sought from its design phase.

5.2 Future Work

- Test different LODs of the virtual model obtained with the BIM methodology to determine its influence on the assessment of sustainability.
- Devise the way to include social indicators within parameters in the virtual model of the BIM methodology
- Study the supposed improvement in the evaluation time due to the application of the proposed new methodology against the traditional way of evaluating sustainability.
- Test the proposed methodology for other types of viaducts and adapt to others types of infrastructure.
- Carry out a sensitivity analysis of the indicators considered in this work.
- Disseminate the methodology proposed in this work to facilitate the evaluation of sustainability in viaduct projects through BIM and MIVES methodologies.
- Use this methodology for decision making studying alternatives to the same project.
- Develop a plugin to include MIVES within REVIT following the process proposed in this work.

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Appendix A

Data of indicators to the case study

A.1 Economic indexes

Total cost

CONCRETE 1 TOTAL COST

<CONCRETE 1 TOTAL COST>

A	B	C	D
MATERIAL: NAME	VOLUME (M3)	COST	TOTAL COST (€)
CONCRETE BEAMS (55 N/MM2)	453.86	121.56	55171.40
CONCRETE FOUNDATIONS (30 N/MM2)	3955.47	90.27	357059.97
CONCRETE SUPERSTRUCTURE (30 N/MM2)	3526.79	96.74	341181.38
Total general: 75	7936.12		753412.75

Figure A.1: Concrete total cost.

STEEL 1 TOTAL COST

<STEEL 1 TOTAL COST>

A	B	C	D	E
MATERIAL	DIAMETER (MM)	VOLUME (M3)	COST	TOTAL COST (€)
B-500 SD	10 mm	4.46	1.17	41000.93
B-500 SD	12 mm	10.02	1.17	92012.28
B-500 SD	16 mm	6.42	1.17	58938.66
B-500 SD	20 mm	19.63	1.17	180325.52
B-500 SD	25 mm	42.59	1.17	391155.14
B-500 SD	32 mm	13.87	1.17	127383.14
Total general: 6064		96.99		890815.68

Figure A.2: Steel total cost.

Indirect cost

CONCRETE 2 INDIRECT COST

<CONCRETE 2 INDIRECT COST>

A	B	C	D
MATERIAL: NAME	VOLUME (M3)	INDIRECT COST	TOTAL INDIRECT COST (€)
CONCRETE BEAMS (55 N/MM2)	453.86	10	5517.14
CONCRETE FOUNDATIONS (30 N/MM2)	3955.47	10	35706.00
CONCRETE SUPERSTRUCTURE (30 N/MM2)	3526.79	10	34118.14
Total general: 75	7936.12		75341.28

Figure A.3: Concrete indirect cost.

STEEL 2 INDIRECT COST

<STEEL 2 INDIRECT COST>

A	B	C	D	E
MATERIAL	DIAMETER (MM)	VOLUME (M3)	INDIRECT COST	TOTAL INDIRECT COST (€)
B-500 SD	10 mm	4.46	10	4100.09
B-500 SD	12 mm	10.02	10	9201.23
B-500 SD	16 mm	6.42	10	5893.87
B-500 SD	20 mm	19.63	10	18032.55
B-500 SD	25 mm	42.59	10	39115.51
B-500 SD	32 mm	13.87	10	12738.31
Total general: 6064		96.99		89081.57

Figure A.4: Steel indirect cost.

Maintenance cost

CONCRETE 3 MAINTENANCE COST

<CONCRETE 3 MAINTENANCE COST>

A	B	C	D
MATERIAL: NAME	VOLUME (M3)	MAINTENANCE COST (€)	TOTAL MAINTENANCE COST (€)
CONCRETE BEAMS (55 N/MM2)	453.86	28.86	13098.44
CONCRETE FOUNDATIONS (30 N/MM2)	3955.47	10.38	41057.74
CONCRETE SUPERSTRUCTURE (30 N/MM2)	3526.79	27.23	96034.41
Total general: 75	7936.12		150190.60

Figure A.5: Concrete maintenance cost.

STEEL 3 MAITENANCE COST

<STEEL 3 MAITENANCE COST>

A	B	C	D	E
MATERIAL	DIAMETER (MM)	VOLUME (M3)	MAINTENANCE COST (€)	TOTAL MAINTENANCE COST (€)
B-500 SD	10 mm	4.46	0.05	1752.18
B-500 SD	12 mm	10.02	0.05	3932.15
B-500 SD	16 mm	6.42	0.05	2518.75
B-500 SD	20 mm	19.63	0.05	7706.22
B-500 SD	25 mm	42.59	0.05	16716.03
B-500 SD	32 mm	13.87	0.05	5443.72
Total general: 6064		96.99		38069.05

Figure A.6: Steel maintenance cost.

Dismantling cost

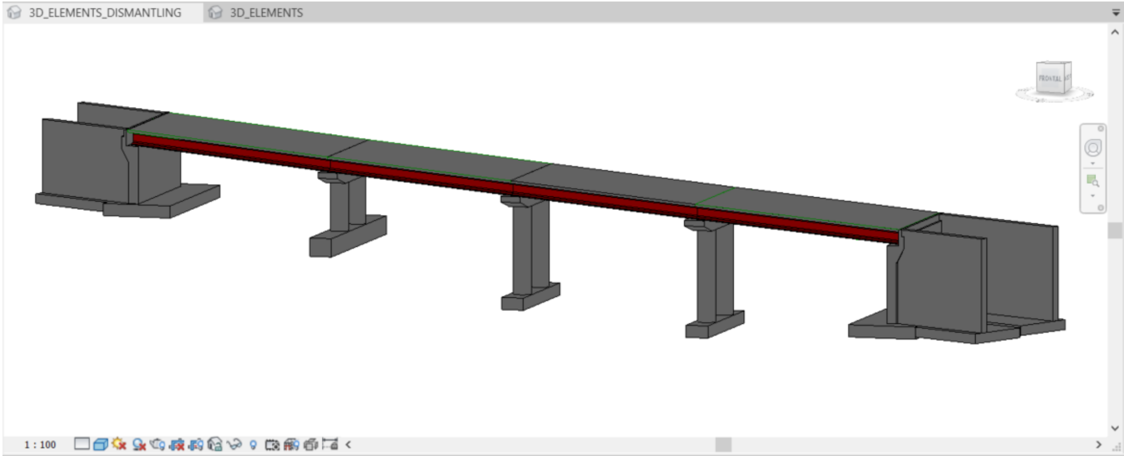


Figure A.7: Structural parts considered to be dismantled of “Las Arenas Viaduct”.

CONCRETE 4 DISMANTLING COST

<CONCRETE 4 DISMANTLING COST>			
A	B	C	D
MATERIAL: NAME	VOLUME (M3)	DISMANTLING CO	TOTAL DISMANTLING COST (€)
CONCRETE BEAMS (55 N/MM2)	453.86	41.95	19039.49
CONCRETE FOUNDATIONS (30 N/MM2)	3955.47		0.00
CONCRETE SUPERSTRUCTURE (30 N/MM2)	3526.79	41.95	147948.72
Total general: 75	7936.12		166988.20

Figure A.8: Dismantling cost.

Execution time

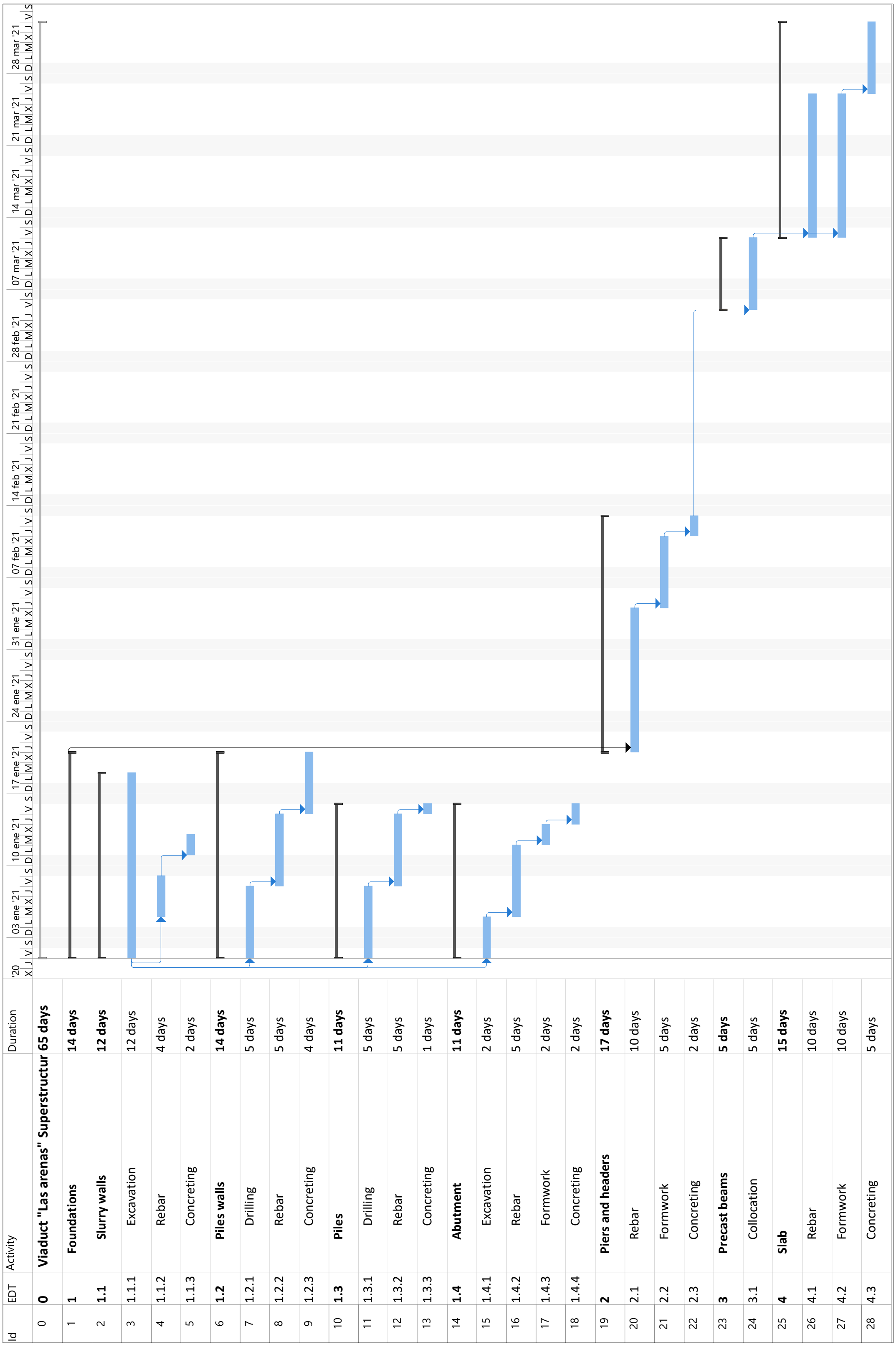


Figure A.9: Plan execution project, “Las Arenas Viaduct”.

A.2 Environmental indexes

CO_2 Emissions

CONCRETE 6 CO2 EMISSIONS

<CONCRETE 6 CO2 EMISSIONS>

A	B	C	D
MATERIAL: NAME	VOLUME (M3)	CO2 EMISSIONS	TOTAL CO2 EMISSIONS (KG)
CONCRETE BEAMS (55 N/MM2)	453.86	275.91	125224.92
CONCRETE FOUNDATIONS (30 N/MM2)	3955.47	265.29	1049345.75
CONCRETE SUPERSTRUCTURE (30 N/MM2)	3526.79	265.29	935621.33
Total general: 75	7936.12		2110192.00

Figure A.10: Concrete CO_2 emissions.

STEEL 6 CO2 EMISSIONS

<STEEL 6 CO2 EMISSIONS>

A	B	C	D	E
MATERIAL	DIAMETER (MM)	VOLUME (M3)	CO2 EMISSIONS	TOTAL CO2 EMISSIONS (KG)
B-500 SD	10 mm	4.46	2.82	98822.75
B-500 SD	12 mm	10.02	2.82	221773.18
B-500 SD	16 mm	6.42	2.82	142057.29
B-500 SD	20 mm	19.63	2.82	434630.74
B-500 SD	25 mm	42.59	2.82	942784.19
B-500 SD	32 mm	13.87	2.82	307026.04
Total general: 6064		96.99		2147094.20

Figure A.11: Steel CO_2 emissions.

Raw material consumption

CONCRETE 7 RAW MATERIAL

<CONCRETE 7 RAW MATERIAL>

A	B	C	D
MATERIAL: NAME	VOLUME (M3)	RAW MATERIAL CONSUMPTION	TOTAL RAW MATERIAL CONSUMPTION (KG)
CONCRETE BEAMS (55 N/MM2)	453.86	2472.00	1121945.55
CONCRETE FOUNDATIONS (30 N/MM2)	3955.47	2374.00	9390277.82
CONCRETE SUPERSTRUCTURE (30 N/MM2)	3526.79	2374.00	8372592.41
Total general: 75	7936.12		18884815.77

Figure A.12: Concrete raw material consumption.

STEEL 7 RAW MATERIAL

<STEEL 7 RAW MATERIAL>

A	B	C	D	E
MATERIAL	DIAMETER (MM)	VOLUME (M3)	RAW MATERIAL CONSUMPTION	TOTAL RAW MATERIAL CONSUPTION (KG)
B-500 SD	10 mm	4.46	1.15	40300.06
B-500 SD	12 mm	10.02	1.15	90439.42
B-500 SD	16 mm	6.42	1.15	57931.17
B-500 SD	20 mm	19.63	1.15	177243.03
B-500 SD	25 mm	42.59	1.15	384468.73
B-500 SD	32 mm	13.87	1.15	125205.65
Total general: 6064		96.99		875588.06

Figure A.13: Steel raw material consumption.

Energy consumption

CONCRETE 8 ENERGY

<CONCRETE 8 ENERGY>

A	B	C	D
MATERIAL: NAME	VOLUME (M3)	MATERIAL: ENERGY CONSUMPTION	TOTAL ENERGY CONSUMPTION (MJ)
CONCRETE BEAMS (55 N/MM2)	453.86	1453.71	659782.96
CONCRETE FOUNDATIONS (30 N/MM2)	3955.47	1421.96	5624515.35
CONCRETE SUPERSTRUCTURE (30 N/MM2)	3526.79	1421.96	5014950.08
Total general: 75	7936.12		11299248.39

Figure A.14: Concrete energy consumption.

STEEL 8 ENERGY

<STEEL 8 ENERGY>

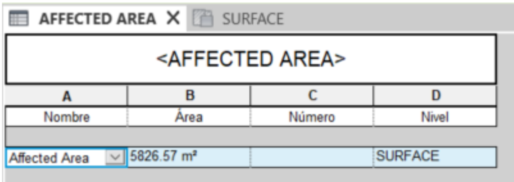
A	B	C	D	E
MATERIAL	DIAMETER (MM)	VOLUME (M3)	ENERGY CONSUMPTION	TOTAL ENERGY CONSUMPTION (MJ)
B-500 SD	10 mm	4.46	35	1226523.51
B-500 SD	12 mm	10.02	35	2752504.00
B-500 SD	16 mm	6.42	35	1763122.42
B-500 SD	20 mm	19.63	35	5394353.21
B-500 SD	25 mm	42.59	35	11701222.19
B-500 SD	32 mm	13.87	35	3810606.89
Total general: 6064		96.99		26648332.23

Figure A.15: Steel energy consumption.

A.3 Social indexes

Affected area

The value of the affected area was obtained from the BIM model carried out in the first phase of the application of the case study. The BIM model allows obtaining the information through an area plan in which the works area is delimited, this area is automatically quantified and is presented in the table of quantities (figure A.16).



A	B	C	D
Nombre	Área	Número	Nivel
Affected Area	5826.57 m²		SURFACE

Figure A.16: Value of the affected area by the construction of the "Las Arenas Viaduct".

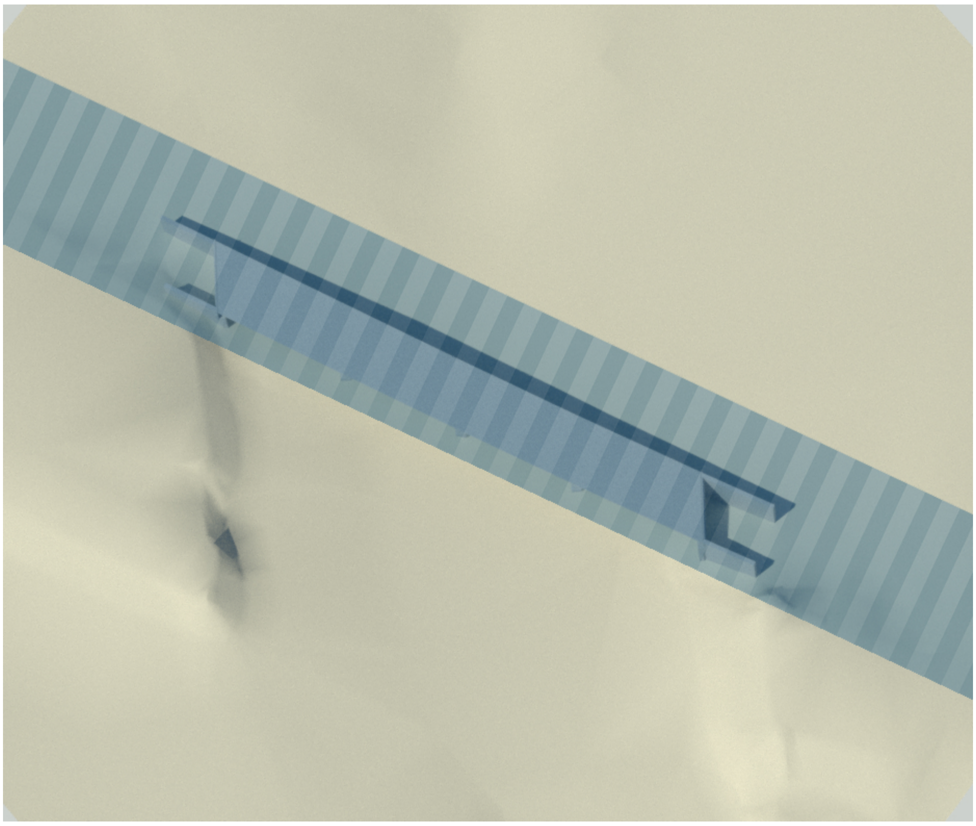


Figure A.17: Affected area by the construction of the "Las Arenas Viaduct".

The shaded area in figure A.17 indicates the area affected by the construction of the viaduct.

Table A.1: General disturbances weights and points.

Indicator	Weight	Level	Points
Noise	60%	Low	10
		Mid	5
		High	0
Traffic	30%	Low	10
		Mid	5
		High	0
Transit	10%	Low	10
		Mid	5
		High	0

Table A.2: General disturbances points for the study case.

Indicator	Level	Points
Noise	High	0
Traffic	Mid-Low	8
Transit	Low	10
Total		**3.40**

General disturbances

Health and safety

Table A.3: Relative risk of each activity [4].

Risk - activity	Standardized weight
Falls to lower levels - work at heights or depths of more than 2 m	
Conventional formwork	0.105
Self-climbing formwork for piles or dams	0.150
Steel-tube scaffold	0.098
Placement of concrete slabs and reinforcement-laying and concrete-pouring work on the deck of a bridge	0.060
Collision with or entrapment by a moving load due to its movement or detachment - mechanical load handling	
Other means of mechanical load handling	0.020
Blows to upper and lower limbs - manual load handling	
Beams	0.060
Installation of reinforcing bars	0.021
Collision with or running over by heavy equipment or heavy-goods vehicles - work with heavy equipment or heavy-goods vehicle	0.068
Burns - welding	0.007
Drowning - work in areas at risk of flooding	
Collision with or running over by vehicles unrelated to the construction work work in areas with traffic unrelated to the construction work	0.058
Traffic accident - transport of elements to the construction site	
Precast pieces	0.090
Concrete	0.040
Steel (structural and reinforcing bars)	0.030
Structural risk or macrorisk - complex operations or structures	0.050

Table A.4: Occupational Risk Index for the case study.

	Risk - activity - subactivity	Standardized weight	Exposure (h)	# Workers	Total Exposure (h)	ORI
1	**Falls to lower levels - work at heights or depths of more than 2 m**					
1.1	Conventional formwork					
	Abutment					
	Formwork	0.105	16	6	96	10.08
	Slab					
	Formwork	0.105	80	8	640	67.2
1.2	Self-climbing formwork for piles or dams					
	Piers and headers					
	Formwork	0.15	40	10	400	60
1.3	Steel-tube scaffold					
	Abutment					
	Rebar	0.098	40	8	320	31.36
	Formwork	0.098	16	6	96	9.408
	Concreting	0.098	16	8	128	12.544
	Piers and headers					
	Rebar	0.098	80	12	960	94.08
	Formwork	0.098	40	10	400	39.2
	Concreting	0.098	16	8	128	12.544
	Precast beams					
	Collocation	0.098	40	10	400	39.2
1.4	Placement of concrete slabs and reinforcement-laying and concrete-pouring work on the deck of a bridge					
	Slurry Walls					
	Concreting	0.06	16	6	96	5.76
	Piles walls					
	Concreting	0.06	32	2	64	3.84
	Piles					
	Concreting	0.06	8	3	24	1.44
	Abutment					
	Concreting	0.06	16	8	128	7.68
	Piers and headers					
	Concreting	0.06	16	8	128	7.68
	Slab					
	Concreting	0.06	40	12	480	28.8
2	**Collision with or entrapment by a moving load due to its movement or detachment - mechanical load handling**					
2.1	Other means of mechanical load handling					
	Slurry Walls					
	Rebar	0.02	32	6	192	3.84
	Concreting	0.02	16	6	96	1.92
	Piles walls					
	Rebar	0.02	40	6	240	4.8
	Piles					
	Rebar	0.02	40	6	240	4.8
	Piers and headers					
	Rebar	0.02	80	12	960	19.2
	Precast beams					
	Collocation	0.02	40	10	400	8
3	**Blows to upper and lower limbs - manual load handling**					
3.1	Beams					
	Precast beams					
	Collocation	0.06	40	10	400	24
3.2	Installation of reinforcing bars					
	Slurry Walls					
	Rebar	0.021	32	6	192	4.032
	Piles walls					
	Rebar	0.021	40	6	240	5.04
	Piles					
	Rebar	0.021	40	6	240	5.04
	Abutment					
	Rebar	0.021	40	8	320	6.72
	Piers and headers					
	Rebar	0.021	80	12	960	20.16
	Slab					
	Rebar	0.021	80	12	960	20.16
4	**Collision with or running over by heavy equipment or heavy-goods vehicles - work with heavy equipment or heavy-goods vehicle**					
	Slurry Walls					
	Excavation	0.068	96	4	384	26.112
	Concreting	0.068	16	6	96	6.528
	Piles walls					
	Drilling	0.068	40	4	160	10.88
	Concreting	0.068	32	2	64	4.352
	Piles					
	Drilling	0.068	40	3	120	8.16
	Concreting	0.068	8	3	24	1.632
	Abutment					
	Excavation	0.068	16	4	64	4.352
	Concreting	0.068	16	8	128	8.704
	Piers and headers					
	Concreting	0.068	16	8	128	8.704
	Precast beams					
	Collocation	0.068	40	10	400	27.2
	Slab					
	Concreting	0.068	40	12	480	32.64

Table A.4 Occupational Risk Index for the case study.

	Risk - activity - subactivity	Standardized weight	Exposure (h)	# Workers	Total Exposure (h)	ORI
5	**Burns - welding**					
	Slurry Walls					
	Rebar	0.007	32	6	192	1.344
	Piles walls					
	Rebar	0.007	40	6	240	1.68
	Piles					
	Rebar	0.007	40	6	240	1.68
	Abutment					
	Rebar	0.007	40	8	320	2.24
	Formwork	0.007	16	6	96	0.672
	Piers and headers					
	Rebar	0.007	80	12	960	6.72
	Formwork	0.007	40	10	400	2.8
	Slab					
	Rebar	0.007	80	12	960	6.72
	Formwork	0.007	80	8	640	4.48
6	**Drowning - work in areas at risk of flooding**					
6.1	Collision with or running over by vehicles unrelated to the construction work work in areas with traffic unrelated to the construction work					
	Slurry Walls					
	Excavation	0.058	96	4	384	22.272
	Piles walls					
	Drilling	0.058	40	4	160	9.28
	Piles					
	Drilling	0.058	40	3	120	6.96
	Abutment					
	Excavation	0.058	16	4	64	3.712
7	**Traffic accident - transport of elements to the construction site**					
7.1	Precast pieces					
	Precast beams					
	Collocation	0.09	40	10	400	36
7.2	Concrete					
	Slurry Walls					
	Concreting	0.04	16	6	96	3.84
	Piles walls					
	Concreting	0.04	32	2	64	2.56
	Piles					
	Concreting	0.04	8	3	24	0.96
	Abutment					
	Concreting	0.04	16	8	128	5.12
	Piers and headers					
	Concreting	0.04	16	8	128	5.12
	Slab					
	Concreting	0.04	40	12	480	19.2
7.3	Steel (structural and reinforcing bars)					
	Slurry Walls					
	Rebar	0.03	32	6	192	5.76
	Piles walls					
	Rebar	0.03	40	6	240	7.2
	Piles					
	Rebar	0.03	40	6	240	7.2
	Abutment					
	Rebar	0.03	40	8	320	9.6
	Piers and headers					
	Rebar	0.03	80	12	960	28.8
	Slab					
	Rebar	0.03	80	12	960	28.8
8	**Structural risk or macrorisk - complex operations or structures**					
	Global	0.05	520	10	5200	260
					ORI	**1188.51**